THE PHYSICS OF MUSIC

BY

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FOREWORD.

Books on the Physics of Music written with the background of European music are in existence. But a book on the same subject written with the background of Indian music has been a long felt desideratum. The author with his long experience in teaching the subject is specially equipped for writing such a book. The Physics of music is one of the interesting branches of Musicology. The gramophone, radio and film are three of the welcome gifts of modern science to humanity. The struggles through which scientists had to pass through before getting at some of the mysteries of Nature are inspiring to read. The subject of Indian instruments too is of absorbing interest, though much work has not yet been done in this field so far. The treatment of the several topics in the book is clear and interesting. The book will be of use not only to students of music but also to the practising musicians.

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INTRODUCTION.

Mr. R. K. Viswanathan, Senior Lecturer in Physics, has been teaching 'Acoustics' to the Sangeetha Bhushana students for the last fifteen years. He is also a keen student of South Indian music and its scientific aspect. He wrote a book in Acoustics in Tamil for the music students, about a decade back. This book was published by the University and is used as a text book by the Sangeetha Bhushana students. With the knowledge gained by long experience he has now written a book "The Physics of Music" in English. This book covers the border land between Music and Physics which could be dealt with only by one whose knowledge extends to both subjects. The book is written in non-technical language so that it may be used by a layman who is not well versed with the technicalities of music nor in that of Physics. Mr. Viswanathan is offering this book for publication by the University. I recommend that his offer may be accepted.

T. P. NAVANITAKRISHNAN,
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PREFACE.

THE basis of all Fine Arts is an attempt to express beauty in form or colour or sounds. A cultivated mind can discover this beauty just as it is able to discover Truth and Goodness. Though the appeal of all arts is primarily to our emotions we should not minimize its appeal to our intellect. Every work of Art, if its beauty were to be appreciated fully, must be considered from two points of view, *viz.* the objective and the subjective. Only through his objective work does the artist make us perceive the beauty in his art. This objective side can be studied leisurely in all arts except music; while the other arts are static, music alone is dynamic. The volatile character of the sound makes it difficult to be perceived leisurely. Very often, one has to hear the same piece many times before one can comprehend its objective side. It is only by giving the closest attention and consciously regarding the piece as a whole that we can derive the maximum aesthetic enjoyment. There are some who believe that there are three levels of appreciation for any Art, *viz.*, the physical, the physiological and the psychical.

More than all other arts, music has always evoked an immediate and forceful response from men in every land and in every stage of mental growth and education. Apart from the technique of musical form and principles, an analysis of any

musical composition will show the three distinct elements, melody, harmony and rhythm on the objective side.

Melody arises when a series of musical sounds rise and fall in pitch by definite intervals upon a rhythmic background. Only certain series of sounds captivate us and keep us thrilled. This mystery can be unravelled to a certain extent by an analysis of the tonal relationship of the various sounds that constitute the melody. A full knowledge of the principle of tonality and its peculiarities is very essential for our aesthetic enjoyment. Tonality is the relating of every sound in the melody to the tonic of the scale in which the melody is sung.

This relationship between the tonic and the successive sounds also gives rise to harmony which assumes very great importance in European music in which a number of sounds are produced simultaneously. Of these two elements harmony has been better understood on the objective side. The composers of western music have made full use of this knowledge.

The third element, rhythm, was historically the first to be noticed in the music of any country. It must be accorded the honour of antiquity. Its appeal is more to the emotions than to the intellect. That is why primitive music is predominantly rhythmical. Response to rhythmical stimulus is instinctive in us because it permeates the whole

realm of our activities both voluntary and involuntary. With the growth of music the intellectual content of rhythm has become considerable. The large number of intricate time-measures in Carnatic music will easily convince any one that rhythm involves considerable thought and alertness in execution.

Though European music shows very striking and characteristic differences from Carnatic music there is one fundamental principle underlying both. Each limits itself to a definite scale or series of notes and its music proceeds from note to note by determinate steps. These steps are measured by the musical intervals. There were originally seven notes to the octave but they have been increased in the course of time. European music has stopped with twelve notes to the octave and with major and minor scales. This has left their composers free to modulate into a different key for the sake of variety and to return again to the original key. In their desire for extending the possibilities of modulation they have abandoned correct intonation. On the other hand, Carnatic music has not only kept correct intonation but has included a wide range of microtonal variations in pitch. It has developed the melody modes or ragas to an astounding degree. In European music the development of scales and the devices adopted for modulation have all been well understood on the objective side which cannot be said of the various ragas in Carnatic music. There is ample scope

for studying the objective side of these ragas. The essence of our music will be missed if this study is not made. In European music an understanding of the phenomena of consonance and dissonance on the objective side has made the choice of consonant intervals very easy. It is claimed that the present progress in European music would not have been possible without this knowledge. The objective side of rhythm has been understood in both the systems of music. The time measures used in European music differ considerably from those used in Carnatic music. Very often complicated time-measures are used in the latter. All these have been systematically classified. The Sangeetha Ratnakara, a well-known treatise on Carnatic music, gives 120 types of different time measures. It is said that many of them have become obsolete now. The prevailing classification has seven talas each of which has five jatis or classes. The five jatis are further classified according to the number of aksharas. To play all these time-measures the technique of percussion instruments has been developed to an enormous degree in Carnatic music. Thus rhythm is more intricate in Carnatic music than in European music. A comparative study of the objective side of the three elements, melody, harmony and rhythm in both the systems of music will certainly contribute to the improvement of both. Such a knowledge is invaluable for the makers of musical instruments.

It is true that the present high standard of excellence in some of them has been attained only empirically. There can be no doubt that a scientific examination of the various parts of a musical instrument will help us to make it still more perfect. The sound producing parts of a musical instrument in general perform two distinct functions. Some parts are designed for the production of musical vibrations; others receive these vibrations and amplify them by resonance. The resulting sounds depend largely upon the kind of sympathy existing between the various parts of the instrument. Western scientists, particularly Helmholtz and D. C. Miller, have done remarkable investigations for their instruments. But in India that line of research is yet to be pursued. Almost all our instruments in use now have not been altered in the smallest detail from their ancient forms. The manufacture of these instruments is still in the hands of ordinary cabinet-makers who are ignorant of elementary acoustics. Considerable improvement is possible both in the shape and material of these instruments which, when made, is bound to react favourably on the quality of the sounds elicited. This book has been written to create an interest in such a study to bring about that much-needed improvement in our music and musical instruments. I am thankful to the Vice-Chancellor and the Syndicate for having permitted the publication of this book by the University.

R. K. VISWANATHAN.

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5. ALAYAMANI.
6. VIGNANA KATCHI.
7. VISVARUPAM.

VIBRATION AND WAVES

CHAPTER I

The sense of hearing and the sense of sight are the most important of the human senses. The enjoyment of music and the visual arts is made possible only through these two senses. But for them we will be denied the highest æsthetic pleasures. We learn a great deal about the world around us through the organs of sight and hearing. In fact, we rely for our very existence on these organs. The phenomena of Sound and Light have many things in common both in their origin and propagation. This has helped investigations of their nature. The study of sounds for the sake of music is claimed to be as old as the human race. Though the musicians of ancient times had accumulated a vast store of knowledge, the subject came to be studied scientifically only during the last three or four centuries.

Sound has its origin in the vibration of material bodies. Material bodies are of three kinds, *viz.* solids, liquids and gases. When the vina is played its strings, its hemispherical bowl, stem and gourd all vibrate and emit sound. These are all solid bodies. If Jalatarang is played there is vibration in the water in addition to the vibration of the sides of the porcelain cups. In the flute and other wind instruments air is made to vibrate.

Vibration is a type of motion. It can be seen plainly in some cases. For instance the vibrations of the string of a vina can be seen by its blurred outline. We can feel these vibrations when a brass tumbler is hit with a small stick. The simplest type of vibratory motion is known as the simple harmonic motion. An example of this type is the motion of a pendulum. The first feature we notice is that it is periodic, repeating its movements regularly. At the two extremes of the movement the pendulum remains at rest for an instant. As it swings, the pendulum will be found to pass the central position with maximum speed. One complete to and fro motion is called a vibration. The time taken for one vibration is termed as its period and the number of such vibrations taking place per second is known as the vibration frequency. The extent through which the pendulum goes to the right or left from the central position is called the amplitude of the motion. All these features are found in the vibrations that give rise to musical sounds.

Musical sounds in general are produced by complicated vibrations unlike the motion of the pendulum. For instance, the violin string on being bowed also vibrates. But this motion is very different from the vibration of the pendulum. While the pendulum swings from right to left with a uniform motion, the violin string vibrates with jerks. When the bow is applied the string clings for a time to the bow and is carried away with itl After some time it suddenly releases itself and

moves against the direction of the bow. Again it is caught and carried forward. This happens regularly. In periodicity, this is similar to the pendular motion. But the way in which the speed of the string changes during a vibration is in marked contrast to that of the pendulum. For this reason the vibration of the violin string is complicated. This complexity depends on other factors also. If, instead of bowing, the string is plucked as in the case of the vina the complexity becomes different. A similar thing happens when the string is struck as in the piano instead of being plucked or bowed. In this way almost all the vibrations which produce musical sounds are complicated for one reason or other. Though they are complicated they can be resolved into simple pendular vibrations.

There are three elements which determine a musical sound. Musical sounds arrange themselves in a natural order according to pitch. Differences of pitch called intervals came to be recognised long long ago by musicians. Musicians of ancient times knew also that a rapid vibration produced a tone of high pitch and a slow vibration produced a tone of low pitch. This was verified later on by a number of experiments and it was conclusively proved that the greater the vibration frequency the higher is the pitch. The other two elements are loudness and quality. The loudness of a musical sound depends entirely on the extent of the vibratory movement. If this is increased loudness is also increased. The larger the amplitude of the vina string the louder is the sound produced. It will be

found also that the same note produced by a number of instruments with the same degree of loudness exhibits differences of character. These differences are known as the differences in quality. The quality of a musical sound cannot evidently depend either on vibration frequency or its amplitude. The manner in which the vibration is induced was found to be responsible for this third element. It is determined by the complexity of the vibration. It was Helmholtz who brought this element from an empirical to a scientific basis by his clasical researches.

Vibrations may be either free or forced. The vibration of a body is said to be free when the exciting cause is removed immediately. When a pendulum is drawn aside and then released or a vina string is plucked, the vibration in each case is a free vibration. The violin string on the other hand makes a forced vibration because the bow is always acting on the string urging it to move alternatively back and forth. Here the exciting cause is not periodic and hence the string vibrates with its natural frequency. Hence this is called a maintained vibration. There are cases where the outside force or the exciting cause impresses its frequency upon the body that is set in vibration. The resonator box of a violin is an example of this kind of vibration. Here the vibrations of the string urge the body and sides of the box to vibrate in tune with it though the natural frequency of the box is considerably different from that of the string. Strictly this type

of vibration alone is called a forced vibration. Forced vibrations play an important part in the construction of musical instruments. They are used either to amplify the original vibrations or improve their quality. In the case of the violin the vibrations of the string will be inaudible but for the resonator box. The vibrations of the reed in the Nadhaswaram and Clarinet will be harsh and shrill but for the pipes. When a body makes such forced vibrations sometimes it does so with great vigour and ease. The response in this case is known as resonance or sympathetic vibration. A number of interesting consequences of this principle of resonance are mentioned. It is said that once a suspension bridge near Manchester gave way because of sympathetic vibrations. It seems a body of men marched in step along the bridge. The footsteps of these marching men started violent vibrations in the bridge which ultimately gave way. It became a rule thereafter that troops must break step whenever they cross bridges.

Sound vibrations are conveyed by material bodies from one place to another. The passage of sound along a solid is very well illustrated by the sounds heard in the water pipes in our houses when the tap is opened or closed. When two stones are knocked together under water the sound of the blow can be heard by a person immersed in water. This demonstrates that sound is conveyed by water. Based on the transmission of sound in water there are a number of devices in use now

for detecting the positions of submarines. For transmission in air the famous experiment of Tyndal is the best proof. In that experiment an electric bell is carefully suspended by means of thin cotton threads inside a bell-jar of an air pump. As the air is pumped out the bell will appear to ring more or more feebly until at last it altogether ceases to be heard. When air is again readmitted the sound of the bell will be found to recover its original loudness. The air of the atmosphere is the most common medium for transmission of all the sounds we hear. Sound travels at different rates through different substances. It has been found that it travels at the rate of eleven hundred feet per second in air. In water its speed is nearly four times that of air. In iron it travels about fifteen times as fast as it travels in air.

This transmission is done by means of waves. Everyone would have noticed the expanding circles upon still water when a small pebble is dropped in it. If pebbles are dropped regularly one can notice a set of curved shapes called crests and troughs advancing one after the other on the surface of water. The crest is the place where part of the water has risen above the original level and the trough is the place where part of the water has sunk below its level. A cork floating near the place of disturbance will be found to remain in the same place riding over a crest and sinking under a trough as the waves advance. So we get an impression of a forward motion although the individual particles only vibrate up and down.

Fig 1 Transverse and Longitudinal displacements

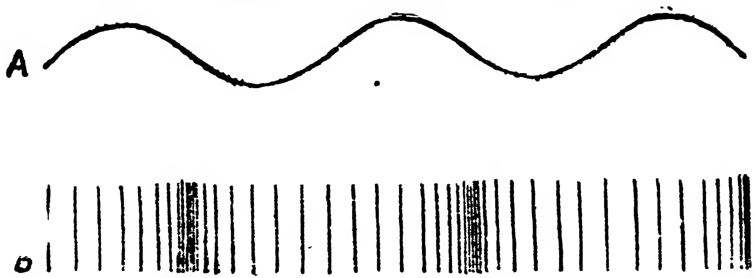


Fig. 2 Transverse wave and wave of compression

It is this apparent translatory motion which is referred to when we speak of advancing waves. This kind of waves is known as transverse waves since the direction of vibration of each particle is at right angles to the direction of advance of the waves. Sound spreads in air in the same manner as the water waves but the advancing waves are not transverse waves. Sound waves in air consist of alterations of condensation and rarefaction. The vibrating body in moving forward compresses the air in front of it. This compression is communicated to the next layer and so on it spreads in the medium. When the source moves backwards it sends out a region of rarefaction behind the compression. This in turn is followed by another compression when the vibrating body moves forward again. Thus in this way a series of condensations and rarefactions advance from the vibrating body. As the particles of air vibrate in the same line as the direction of advance of the waves this type of waves is called compressional waves. Solid bodies can transmit both transverse and compressional waves while compressional waves alone can travel in air. Though sound waves in air cannot be seen they can be understood by an analogy. Anyone who has observed a paddy field when the crop is standing erect would have noticed a thrill running along their tops whenever there is a wind blowing. This thrill is nothing but a set of compressional waves. As they travel it will be noticed that the grains move only to and fro in the same direction as the advance of these waves. A similar thing happens when sound waves travel in air.

Though the two types of waves differ in the direction of particle vibration there are certain common features like wave-length, wave-amplitude, wave-frequency, wave-velocity and wave-shape etc. In the case of transverse waves one crest and one trough together form one complete wave. The distance between two neighbouring crests or troughs is known as the wave-length. In the case of the compressional waves one condensation and one rarefaction form one complete wave while the distance between two neighbouring condensations or rarefactions is called the wave-length. The wave-amplitude denotes the extreme distance that each particle of the medium moves from its mean position in both the types. In the case of water waves we generally call the vertical distance between the crest and trough the height of the wave and this is twice the wave-amplitude. The number of vibrations made by each particle of the medium as the waves advance is known as the wave-frequency. The rate at which these waves advance in the medium is known as the wave velocity. The magnitude of this velocity is dependent on the elasticity and density of the medium. There is a close relation between the wave-velocity, the wave-length and the wave-frequency. The shape of these waves is determined by the mode of vibration of the particles of the medium. It has been shown that the wave-shape is an indication of the quality of the musical sound.

Sound waves are subject to reflection and refraction as in the case of light. For example,

echoes are due to reflection. An echo will be heard only when the reflecting surface is far away. It has been observed that the surface has to be at least beyond thirty-five feet from the observer for the echo to be heard. If the reflecting surface is curved it may cause the sound waves to converge to a focus. The effect of the whispering galleries in certain buildings is explained only by such focussing action. Refraction happens when the sound waves reach an interface between two different media because the wave-velocity changes from one medium to another. A change in temperature in the different parts of the atmosphere may also bring about refraction for sound waves travel faster in warmer air than in cooler air. The refraction caused by temperature variation is very similar to the optical phenomenon of mirage. Wind also produces refraction of sound waves. It is a familar observation that sound waves travel better with the wind than against it. Near the ground the wind meets more obstacles than it does higher up. This makes the velocity of the sound waves alter as we go up from ground level to a higher altitude which brings about the refraction. Sound waves unless they are of high frequency do not cast shadows when they meet with obstacles. Two trains of sound waves when they meet may interfere in such a way that they neutralise in certain places and assist in others. Thus sound waves have many interesting characteristics. In conclusion it can be said that a study of sound is merely a study of vibrations and waves.

CHAPTER II

VOICE

Voice training is an art by itself though its significance has not been fully recognised by our musicians. It is well known that among distinguished vocalists of our day only a few have been endowed with good voices. That a good voice is the first requisite for a vocalist is not always realised by us. It is true that not everybody is lucky enough to possess a rich voice. But it is also true that ordinary voices can be improved considerably by proper training. A knowledge of the Physics of the human voice will be useful in this connection.

The organ by which voice is produced is known as the larynx. It is also popularly known as the voice box. This is situated between the back of the mouth and the top of the wind pipe thus forming the upper part of the tube of communication between the external air and the lungs. Its position is marked by the projection in the throat popularly termed "Adam's Apple." Within this cavity are two horizontally stretched fibrous bands known as the vocal cords; the chink between them is called the glottis. On examination by an instrument known as the laryngoscope, it is found that during deep inspiration the glottis is V-shaped with the vertex directed forwards. This is shown in the figure. When an attempt is made to speak it is found that the edges are brought parallel and

practically into contact with each other. The human voice is able to produce musical notes by the vibration of these vocal cords. Before seeing

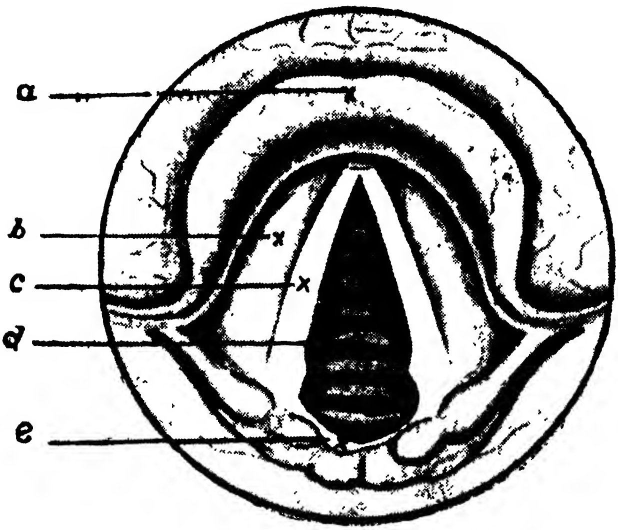


Fig. 3.

Larynx

(*a*) **Epiglottis**
(*b*) **False vocal cords**
(*c*) **True vocal cords**
(*d*) **Trachea**
(*e*) **Anterior wall of the Larynx**

how this is done it is better to know the essential parts of a musical instrument and their functions.

On scrutiny it will be found that every musical instrument is made up of three chief parts, *viz.* (1) the vibratory system (2) the means for increasing the volume of the sound which can be called for our purposes the resonator and (3) the manipulative mechanism for the production of the various notes of the musical scale. Taking for

instance the vina, it is seen that the main and subsidiary strings by their vibration generate the sound which is amplified by the bowl and the stem ; for playing the various notes according to the musical scale the main strings are pressed against the frets by the left hand fingers. Frets are the short brass pieces which are fixed on the two ledges running along each side of the stem of the instrument.

In the vocal organ the lungs act as a kind of bellows increasing the pressure of the air below the cords and the issuing stream sets the vocal cords in vibration. The vibrations are then communicated in turn to the resonant air cavities formed by the larynx, the front and back parts of the mouth separated by the tongue and the nose. Variation in frequency is made possible by the muscles which control the width of the glottis and the tension on the cords. Alterations in intensity of the notes are made by controlling the strength of the current of air through the glottis. The vocal mechanism has been described by some physicists as resembling a stringed instrument and by others it is likened to a wind instrument. In fact it is a combination of both in that it resembles a stringed instrument in its vibrator and a wind instrument in its generator. More recently the view has been put forward that the function of the vocal cords is to induce vortex formation in the stream of air as it passes through the glottis and thus generate the sound. The shrill notes which we hear when the wind blows over the telegraph wires or through

stalks of corn or blades of grass are cited as examples. Anyway the vibration of the vocal cords plays an important part in sound production. In men the natural length of these cords is greater than in women and hence the voice is shriller for women. The familiar phenomenon of the breaking of a boy's voice in his teens is due to the rapid growth of the larynx and the corresponding increase in the length of the cords. The best human voice has a range of three and a half octaves although in practice few people are able to sing in more than two octaves. In men two kinds of voice have been recognised *viz.* "The Chest Register" and "The Head Register". Between these two there is a break in the voice which is disguised by practice. At lower frequency the chest voice is employed. It is found then that the slit between the cords is very narrow and long and that the cords vibrate as a whole. For the higher notes the head voice is employed and in this case it is found that the vocal cords are wider apart with only their innermost margins vibrating.

The characteristic by which we are able to distinguish notes of the same pitch and intensity coming from different instruments is known as "Quality or Timbre". The French mathematician Fourier has enunciated a theorem which states that any type of vibration however complicated can be analysed into a series of simple vibrations of commensurate frequencies. So any musical note can be analysed into partial tones whose frequencies are once, twice, thrice or several times

greater than the prime tone. It has been shown by the distinguished German scientist Helmholtz that the quality of a musical note depends on the number of these partial tones present and their relative intensities. It is the abundance of these overtones that produces the richness of the human voice and gives it the honoured place it occupies among instruments. Another factor which places it in a class apart from all other instruments is the vowel qualities of its tone. It has been found that when different vowels are sung to any note they are characterised by the prominence of one or more partials of definite pitch. This is ascribed to the alterations in the shape of the mouth cavity when the vowels are sung.

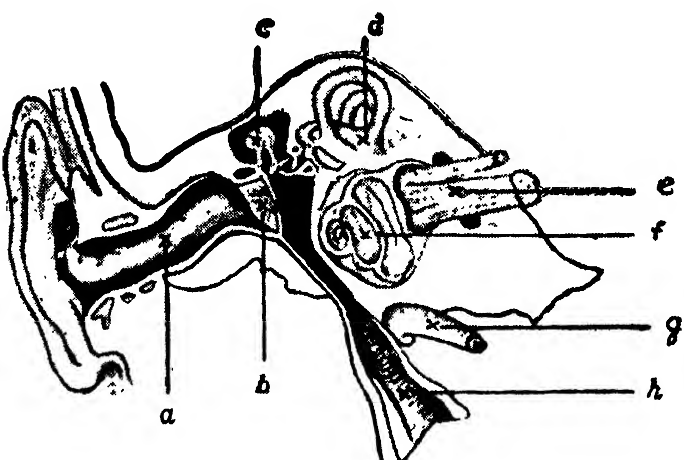
In training the voice, proper control over the muscles regulating the air stream and those concerned in the mechanism of the larynx should be obtained first. One has a certain amount of direct control over the muscles which regulate breathing and also over those which cause movements of the tongue, lips, soft palate etc. The muscles of the larynx cannot be exercised independently. The control over them that makes singing possible depends entirely on the ear and the brain centres connected with it. It is because of this that deaf children can be taught to speak but not to sing. This is also obvious from the fact that one is able to sing ragas perfectly by constant hearing alone without learning the theory of the combinations of notes. If the breathing muscles are not properly controlled extreme unevenness of tone will result.

One should take regular breathing exercises to increase the capacity of the lungs and to render the control of the air supply as complete as possible. The expiratory and laryngeal muscles must act simultaneously. If the air stream precedes the action of the cords the tone becomes breathy since some of the expired air escapes between the cords. If, on the other hand, the laryngeal muscles act before the expiratory muscles, the air arriving at the glottis finds the exit closed and a further pressure of breath must be applied to separate the vocal cords before tone can result. This forcible opening of the glottis produces a "click" in the tone which can be easily found out. This fault is known as "Throatiness." This is most harmful as it unnecessarily fatigues the throat and gives the singer an agonised expression. If it is not corrected it may result in a very common disease among singers known as "singer's nodules" in the throat. It is suggested that humming exercises are often useful for curing this fault. For general guidance to beginners it may be said that if the voice effort is felt in the throat it is certain that the production is wrong. If, however, the singer is not conscious of effort in the throat but feels that the voice initiates at the waist, and that it is being produced in the chest it indicates that the production is correct)

CHAPTER III

EAR

The mechanism of hearing is a subject which touches various branches of science. The ear as a physical instrument possesses remarkable characteristics; it stands foremost among all the receivers of sound. Its powers of analysis, its sensitiveness over wide ranges of intensity and frequency, the perception of direction by means of both the ears and many other phenomena have been accounted for recently.



The Human Ear

(a) External Ear Canal
(b) Drum-Skin
(c) Ossicles
(d) Semi-circular Canals
(e) Auditory nerve
(f) Cochlea
(g) Carotid
(h) Eustachian tube

The human ear may be regarded as divided into three parts; the outer, the middle and the inner ears. The outer ear consists of the external part known as the 'Pinna' leading to the auditory canal and thence to the drum-skin. In the lower animals the Pinna is provided with muscles and is capable of movement which helps them to collect sounds from different directions. The middle ear contains three small bones known for their shapes as the hammer, the anvil and the stirrup. They are also collectively termed 'ossicles'. This chain of bones connects the drum-skin with the small oval window of the inner ear. The behaviour of these three bones is an interesting mechanical study in itself. From the middle ear the Eustachian tube proceeds to the pharynx. The tube opens when swallowing occurs and so helps to equalise pressures on both sides of the drum-skin. This equality is essential to hearing. When one dives under water or goes up in an aeroplane the equality is lost and it may be restored by properly swallowing. The inner ear is a complex structure. It comprises the vestibule, the three semi-circular canals and the Cochlea. The vestibule is the middle part of the inner ear and contains the oval window which receives the foot of the stirrup. Forward and downward from the vestibule we have the important structure the Cochlea resembling the snail's shell. The three semi-circular canals take no part in the mechanism of hearing but serve as an organ of balance. The Cochlea is really the end organ of hearing. It is a spiral cavity in the

bone consisting of two galleries, one over the other, divided by the basilar membrane, and communicating with each other at the far end where there is a break in the basilar membrane. The cavity is filled with a liquid. The basilar membrane has embedded in it a number of fibres varying in length from one end of the membrane to the other. The tensions on them are also found to vary accordingly. A system of nerves known as the auditory nerves connects the Cochlea with the brain.

Sound entering the ear sets up minute changes in the air pressure in the ear canal and these cause the drum-skin to vibrate. This motion then passes through the chain of the tiny bones to the oval window. In this transmission these bones act as a transformer in communicating the vibratory energy from the air, a light medium, into the liquid, a dense medium. There appears to be an attempt here to reduce the displacement and increase the pressure amplitude in transferring these vibrations. That is, the chain of bones after receiving the motion of the comparatively large drum-skin moved by the air, changes it into the more forcible motion of the very small oval window which is communicated to the liquid within.

The processes within the inner ear are not fully understood and many theories have been advanced to explain its function. Of these theories, the resonance theory seems to be accepted by many. According to this theory the vibrations of the liquid in the inner ear affect the basilar

membrane in different portions depending upon the frequency of the incoming sound, the high tones disturbing the thick end of the membrane near the oval window and low tones affecting the other end. Sympathetic vibration then takes place in the fibres in those regions and sensation is carried to the brain by the auditory nerves. Due to the very small dimensions in the ear the frictional forces are very large and consequently the damping is great. But for this heavy damping on the basilar membrane a rapid performance on a musical instrument would be audible as a jangle of notes. It means that vibration in the basilar membrane dies down so quickly that it is able to follow the changes without delay. Experiments on guinea pigs which have been subjected to a continuous sound of a fixed pitch for several hours have revealed that low tones caused a degeneration of the basilar membrane towards the apical end while the high tones caused degeneration near the basal end. Thus the possibility of fatiguing and even permanently injuring a definite portion of the basilar membrane by continued sounding of tones of the corresponding frequency supports the resonance theory. The definite pitch and intensity limits further support the theory.

Of all the special features of the human ear, its power of analysing a complex note stands supreme. As everyone is aware, the ear is particularly sensitive to that characteristic of sound which we call "Quality or Timbre". It has been shown by Helmholtz that 'Quality' depends on the number, intensity and distribution of the harmonic components into which a sound can be analysed.

The ear possesses this remarkable faculty of doing the Fourier analysis of a complex note. It means that within limits depending on the training of our ears we are able to say what partial constituents are present in the note. The minuteness with which a trained ear is able to perceive dissonance between two notes further reveals its subtlety. The highly evolved scales in our systems of music show the way in which the ear is trained.

The range of pitch to which the human ear is sensitive depends upon the individual. It also varies with time for the same person. The lowest frequency sensed as a note is given variously, but may be taken as about 16 vibrations per second. The highest pitch audible is also somewhat uncertain. Some are able to hear sounds upto a frequency of 40,000 per second. The extreme limits can thus be placed between 16 to 40,000 per second. For musical purposes frequencies ranging from 40 to 5000 per second alone are used. Making a comparison with the other sense organ namely the eye it can be observed that while the eye sees only one octave, the ear hears about eleven octaves of which seven are used in music.

Before a tone can give rise to the sensation of hearing, the vibrations must attain a certain minimum amplitude. This minimum amplitude varies with the pitch of the tone. As the amplitude of the sound is increased, the sensation becomes progressively louder until a tickling is experienced. Still higher amplitudes cause actual pain. This sets the upper limit of audibility. The amplitude of a sound wave is usually expressed in terms of aerial pressure. Between these thresholds is the

range of acoustic pressures for which hearing is possible. Commendable work on the determination of these thresholds has been done by Fletcher in the Bell Telephone Laboratories recently. One of the amenities of our civilisation is noise, which is becoming an increasingly important problem. The all-round use of mechanical devices for transport and industrial operations has accentuated the problem especially in cities. Speech at normal conversational level under such conditions will be unintelligible. This is due to the masking effect of the noise. It is necessary to increase the vocal output power from the normal value to one which outmasks the noise. The threshold of hearing is consequently shifted. Quantitative data have been obtained recently regarding the masking of sounds by various investigators working on the problem of noise and its effects.

While a single ear can give some information concerning the direction of a source of sound, the use of both ears is necessary if accuracy is to be obtained. In the case of the eyes they have an additional advantage in that they help us to estimate both the direction and range. The directional properties of the ears are explained in terms of the intensity or phase theory according to the pitch of the tones heard. Thus for high-pitched sounds of short wavelengths these effects are explained by the difference in intensity of the sound reaching the two ears, the head functioning as a screen to the ear farther away from the sound source. At lower frequencies when the wavelength exceeds the circumference of the head the intensity theory alone was not found enough to explain the

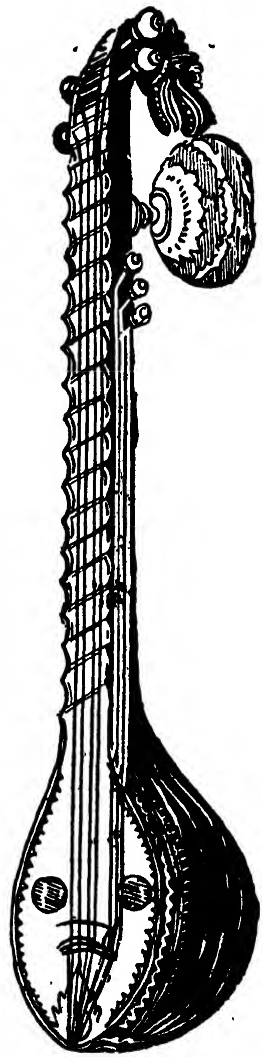
observations. Lord Rayleigh says that the judgement of direction is founded on the difference of phases at the two ears. This binaural faculty which enables us to get an idea of the direction in which a sound source lies was used during the first world war for locating hostile sounds with the aid of intensifying apparatus. The sound whose direction was sought was usually that from an hostile aeroplane. Two long conical trumpets were used as artificial ears. These were mounted with their axes parallel at the ends of a struts several feet long which could be revolved so as to point towards the source. To know both the elevation and bearing of the aeroplane two pairs of trumpets were used. With the help of experienced listeners correct observations were made.

That the ear can manufacture certain tones quite apart from those present outside the ear had been found out as early as the eighteenth century. It was Tartini, the famous violinist, who first noticed that when two notes a fifth apart in the middle of the scale were played on the organ, together with these notes a new low note was heard whose frequency was the difference of the two higher pitched notes. This is now known as the differential tone. To give a familiar example the sound heard from a policeman's whistle is a differential tone. Helmholtz further discovered another tone whose frequency is the sum of the original frequencies. These subjective combinational tones, as they were called, are attributed to the non-linear characteristic of the ear.)

CHAPTER IV

VINA

The vina is an instrument of great antiquity. It commands peculiar veneration and distinction among all our musical instruments. It is a string instrument plucked like the Harp and the Guitar. Though deficient in volume its sound has a captivating tonal quality. No other instrument can approach it in its ability to produce tones which are both rapid and graceful. Its frets are no impediment to eliciting grace notes of infinite variety. Time was when the Vina served as an accompaniment for vocal music in concerts. One will never get tired of hearing "Thanam" for any number of hours on this instrument. It is to this instrument that our Carnatic system of music owes a great deal for settling some of its problems. In spite of its merits however it is lacking in acoustic output.



The Vina

Stringed instruments depend on their sound boards for their intensity. It is obvious that very little sound will be heard from strings rigidly supported.

The air is not compressed before an advancing string and rarefied behind a retreating string but to a great extent slips round from front to back of the string. Hence the strings are fixed on a sound-board to which their vibrations are communicated and as the board has a large surface it is able to pass on its vibrations to the air. We should not merely be interested in the vibrations which the string executes but also in the vibrations which the string forces the sound-board to execute. A double duty is thus thrown on the sound-board of not only reinforcing the string vibrations but also improving them. The design of sound-boards for various stringed instruments is a very complex problem. The precise dimensions of the mechanical details of the string, bridge, sound-board etc. which would secure the desired quality of tone are still settled only on an empirical basis. For this we owe much to the refined taste and the accumulated experience of those concerned in the making of the instruments.

The function of increasing the sound output in the vina is delegated to the large pear-shaped bowl and its associated parts. The bowl is hollowed out of one piece usually of jack-wood or rose-wood. In European stringed instruments much thinner wood like the Maple or Sycamore is used which accounts for better reinforcement of the sound. Tanjore, Trivandrum, Mysore and Miraj are some of the chief centres where these instruments are made. In the northern instrument a hollow gourd resonator is used in the place of the wooden bowl.

The bridge is placed on the centre of the bowl and elaborate precautions are taken to fix it. The upper metal surface is made curved. In addition to this main bridge there is a side-bridge in the form of an arc of brass attached to it. Many small holes are bored in the bowl near the bridge which establish communication between the air outside and inside for purposes of better transmission. The body of the instrument is also made of the same kind of wood as the belly and is hollowed out thin. This part is known as " Dandi ". The body terminates in the neck which is usually curved downward into some weird figure. Into the body just near the neck is fixed a hollow gourd on the underside which forms a kind of rest and also helps the bowl in the reinforcement of the sound. The deficiency in the volume of sound, to a large extent, should be attributed to the massive structure of the belly, body etc. It is possible to increase the output by cutting down the ornamental decorations and using still thinner wood in the construction of the bowl.

There are seven strings of which four pass over the frets and the other three are stretched at the side of the finger-board. The first four strings constitute the main playing strings while the latter are played only to mark the time. As has been pointed out earlier the method of excitement is by plucking, that is, by drawing the tense string out of its position of equilibrium and suddenly letting it go. This is done either by the finger or with a wire plectrum. Just before being let go the string is displaced such that the two portions of the string

make an angle at the plucked point. On being released the string goes through a series of evolutions. Stroboscopic examination reveals that two disturbances travel from the plucked point in opposite directions along the string; they are reflected at the ends and again meet. These evolutions go on continually till the motion dies

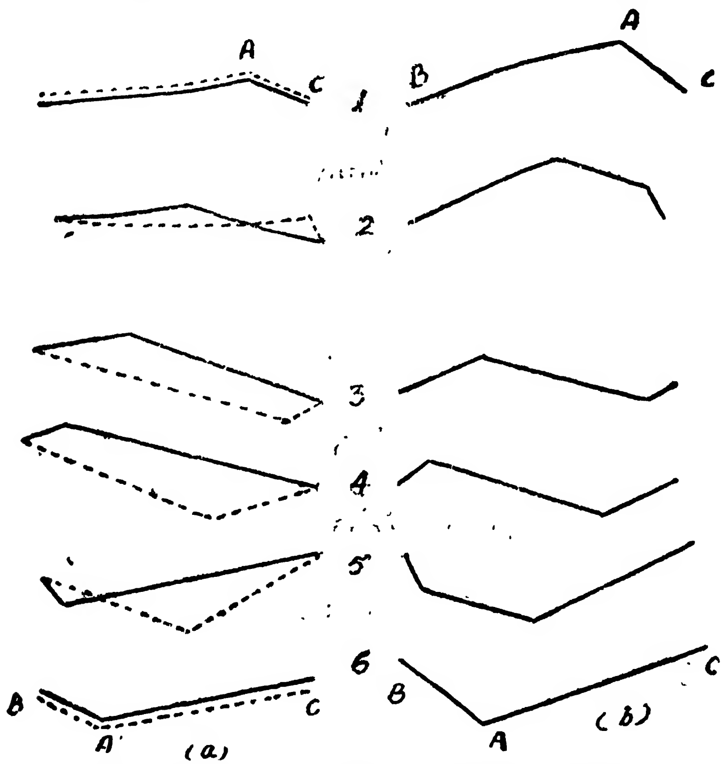


Figure showing the different stages of vibration of a plucked string.

out. Six different stages in half a vibration are represented in the figure, which shows on the left side the individual disturbances and the resultant motion of the string in each case on the right side.

This curve when analysed is found to contain a large number of harmonics subject to certain limitations. The initial curve is not so sharply bent as shown in the figure owing to the width of the finger and this affects the production of higher harmonics. Stiffness of the string, damping due to internal friction and movement of the points of support are some other factors which further affect the wave form and hence the quality of the sound it emits.

The finger-board in this instrument requires special mention. It contains number of frets made of either brass or silver secured to two ledges, running along each side of the stem of the instrument. These ledges are made of some kind of wax which can be melted by heat so that the position of the frets can be altered if necessary. There are twelve frets to the octave and this shows that Equal Temperament* has been in vogue among us from a very long time. Because of the frets it is easy to get proficiency sooner in vina than in other stringed instruments. Tempered intonation nevertheless suffers from a serious drawback. Though the most important intervals the fourth and the fifth are not affected appreciably in the Equal Temperament system the purity of other intervals is sacrificed for purposes of convenient playing. Our system of music depends solely on the purity of intervals. One may wonder how Equal Temperament in the

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* **It consists in dividing the Octave into twelve equal intervals. Thus if $\times$ is the ratio of the frequencies of consecutive notes in this scale, then $\times^{12}=2$ whence,**

vina can suit our Carnatic Music. But the purity of tones is maintained by skilful playing. Slight alterations of pressure upon the frets enable one to secure this. The performer is able to produce graces of all kinds in this instrument in a remarkable manner by means of these frets.

Sir C. V. Raman has investigated the acoustic properties of the "Tambur" and the vina and he has shown how the form of the bridge in each case accounts for the tonal quality of these instruments. He has attempted to give an explanation of the rich overtones of the Tambur when a silken thread of suitable thickness known as "Jeevalam" is slipped between each string and the bridge below it. He points out that by the insertion of this thread a finely adjustable grazing contact of string and bridge is secured. In the vina he has found that the curvature of the upper surface of the bridge ensures the string always leaving the bridge at a tangent. He has also found that the Young-Helmholtz law is not obeyed in both cases. According to the law if a string is plucked at a point of aliquot division the harmonics having a node at the point of excitation should be entirely absent. He has not found this to be the case in these instruments.

$\times = 2^{1/12} = 1{\cdot}059$. The following table gives the actual frequency ratios for the eight principal notes in the octave of the Equal Temperament scale against those of the Sankarabaranam scale.

	C	D	E	F	G	A	B	C'
Equal Temperament ..	1	1·122	1·260	1·335	1·498	1·682	1·888	2
Sankarabaranam ..	1	1·125	1·25	1·333	1·500	1·667	1·875	2

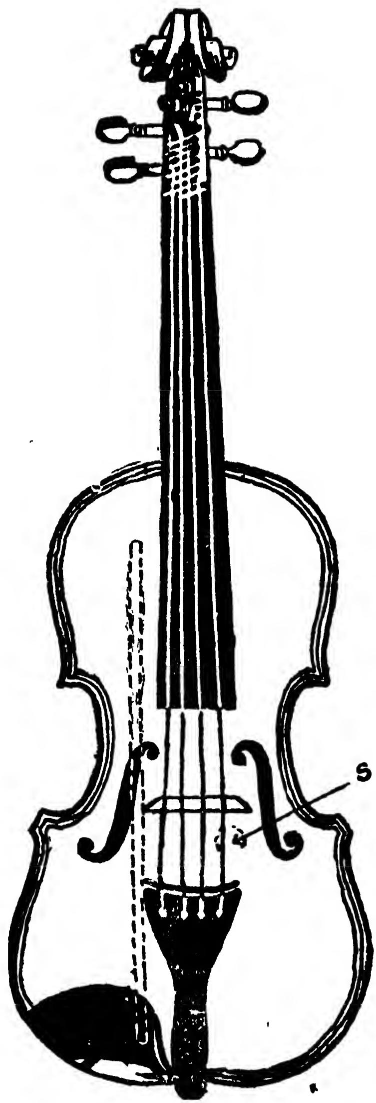
CHAPTER V

VIOLIN

Next to the human voice, for expressive music stringed instruments have found universal favour and pre-eminent among them are those played with a bow. It is interesting to note that friction is here employed as an aid to music. There is an array of bowed instruments in use both among us and in the West. The Sarinda and the Sarangi are claimed to be the best of our indigenous bowed instruments; the violin stands supreme among the western bowed instruments. The invention of the violin bow has been ascribed to us. After our contact with the westerners we have taken two of their instruments, the harmonium and the violin. It is admitted on all hands that the former is thoroughly unsuited for our music and is doing great harm. The latter is distinctly an acquisition and its worth can hardly be over emphasised. The late Tirukodikaval Krishna Iyer and Trichinopoly Govindaswamy Pillai had shown how our Carnatic music stands to gain by that acquisition. No wonder it has displaced our time-honoured instrument, the veena.

The body of the violin consists of a hollow wooden box which is of a peculiar shape necessitated by the movement of the bow. It is provided with two openings known for their shape as *f* holes. The strings are stretched over a bridge which stands

over the most mobile part of the belly between the two '*f*' holes. One foot of the bridge rests on a comparatively firm support known as the "sound-post" which is inserted between the back and belly of the instrument. It is only the other leg which agitates the elastic wooden plates and through them the enclosed mass of air and finally the external air. Thus the sound of the strings is reinforced by the forced vibrations of the box and the air inside it.



The player passes the bow across the strings in order to elicit and maintain the vibrations of the strings. It is essential to apply the bow at right angles to the strings. Otherwise longitudinal vibrations will be set up and the jarring sounds which we often hear when a careless player plays on the violin are due to this. Sometimes these jarring sounds are also produced by a wrong

adjustment between the pressure and the speed of the bow. The vibrations of the string then move the bridge which in turn moves the belly, sides and back of the sound box. Finally the air within the box pulsates in response. Thus sound is radiated from the whole body of the instrument into the surrounding air. Although the string is the source of these vibrations it is only after modification by the different parts mentioned above we hear the note produced by the instrument. The use of the fingers of the left hand to press against the finger-board helps the player to produce the different notes of the musical scale. By diminishing the length of the vibrating string the note is sharpened. The lower frequency limit of the compass is quite definite while the upper limit depends upon the skill of the performer.

Attempts made to develop a theory for the vibrations of the bowed strings have revealed that the problem is very complicated ; it presents many interesting features. The celebrated German Scientist Helmholtz was the first to study the problem and it was our Sir C. V. Raman who finally laid the foundation for the mechanical theory of bowed strings. The action of the bow, the mode of vibration of the strings, the character of the forced vibrations of the bridge and the associated parts of the instrument, the way in which the harmonics are affected by the bowing pressure, speed and width of the region of contact between the bow and the string, are some of the points that were tackled.

Fig. 8

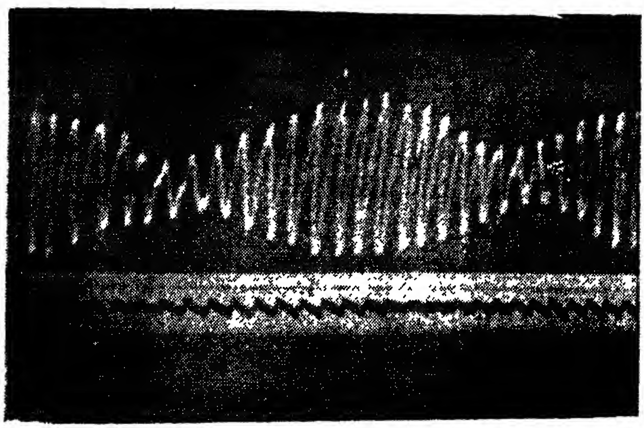
Vibration curve for string showing two step straight line zig-zag.

From a study of forced vibrations it is seen that a steady directive force cannot maintain vibrations undiminished in amplitude. In the violin we see that the bow has no periodic motion and yet it maintains the vibrations in the strings. The explanation given is this. The rosined hairs of the bow first drag the string aside with the bow. In this case it has been shown by Sir C. V. Raman that the string moves with the velocity of the bow. So the full static frictional force is exerted between the string and the rosined hairs of the bow. Initially the tension in the string is at right angles to the frictional force and as the bowed point is pulled aside the components of the tension in the two parts of the string in the direction of the bow oppose the frictional force. When these components become together greater than the frictional force the string ceases to adhere to the bow. String and bow now possess a relative velocity and the dynamical friction involved is less than the static. The components of the tension now drag the string back against the bow to the original position. Owing to inertia it goes beyond this until it is brought to rest by the reversed components of the tension. It is then suddenly caught by the bow

and is dragged with it. Thus while the bow moves continually in one direction the part of the string under it moves to and fro alternately with and against the bow. Further it has been found that both the increase of the bowing speed and pressure raise the general intensity. The effect of the finite width of contact between the bow and the string tends to remove some of the higher harmonics and the quality becomes altered.

With an instrument known as the Vibration Microscope it was shown by Helmholtz that in the simplest case the vibration curve of a point in the string consists of a two step straight line zig-zag. Photographic studies of the vibrating point by Krigar-Menzel, Raman and others confirmed this. In fact, Raman in one of his experiments obtained a complete photographic record of the entire motion of the string. Professor Barton and his pupils further investigated the subject by their photographic studies of the vibrations of different parts of the body *viz.* bridge, belly etc. In instruments of this type it was found that when the pitch of the tone elicited from the string coincides with one of the harmonics of the wooden structure a howling note was produced. This is known as the "Wolf-note." At this pitch the whole body of the instrument vibrates in an unusual degree. The bow refuses to 'bite' the string and bowing becomes difficult. With the object of correlating the vibrations of the belly and string simultaneous records of their motion were obtained at the 'wolf-note' pitch. Again it was Sir C. V. Raman who gave

the correct explanation of this phenomenon. There is one other point to be mentioned here. In order to deaden the intensity of the sound it is usual to load the bridge by a metal clamp known as the 'mute.' Not only does it reduce the general amplitude of the vibrations of the instrument but it gives a new quality to the note. The same thing can be noticed also in the notes of the metal and wooden Nagaswara. How the addition of this load



Fig, 9
Vibration curves for belly and string at the wolf—note pitch.

affects the vibrations has also been studied experimentally. Sir C. V. Raman found a lowering of the 'wolf-note' pitch from 176 to 160 vibrations per second when the bridge was loaded by 17 grams of a metal in the violin he used.

Helmholtz's study of the quality of the violin tones has shown that the strings allow harmonics to be produced as high as the sixth partial tone

with ease and with difficulty even up to the tenth. He found the higher upper partials much more distinct than the others and he is of the opinion that it is these partials that give the cutting character peculiar to the violin tones. In addition to the natural harmonics we have also what are called artificial harmonics. These are produced by pressing the string firmly against the finger-board with one finger and touching it lightly with another finger at a point between the former place and the bridge. Further it is the resonator that gives the instrument its valued quality of tone. It is said, that the wood, the shape and the varnish are of highest importance. Imperfection in the elasticity of the wood is a serious flaw. Much of the advantages of the old violins is due to their long use which affects favourably the elasticity of the wood.

An exact understanding of the minutest details in violin playing is essential to the attainment of violin technique. It is hardly necessary to mention that it is more difficult to attain complete mastery of the violin than other instruments. It is not easy to assess the relative importance of the bow technique and the left-hand technique. The bow plays the part of the voice in vocal music. Just as singing cannot be satisfactory without good voice so violin playing cannot be good without good bowing. Delicate movements of the wrist and arm have to be mastered. It is unnecessary to exert more than a slight pressure to maintain the vibrations. Too much pressure causes a rebound in the strings which will be

difficult to control. The strings must be allowed to vibrate unhampered. Proper adjustment between speed and pressure comes only by long practice. The difference in modes of bowing for rendering swara or sahitya in Carnatic music illustrates one such point in bow technique. The left-hand technique is equally difficult to master. The finger action should be precise and vigorous, that is, the descent of each finger must be as quick as possible in the right place. The usefulness of the violin for playing Carnatic music consists in the sliding action of the hand which helps to produce "Gamakams" with considerable ease. "Graceful rapidity, grave procession, quiet advance, wild leaping, all these different characters of motion and a thousand others in the most varied combinations and degrees" can be produced by this remarkable instrument in the hands of an expert player.

CHAPTER VI

FLUTE

The flute stands out as a typical and important member of the family of wind instruments. The vertical flute was in vogue in very early times; the present day side blown instrument is its successor. Its antiquity among us can be judged from the fact that this instrument is associated with the puranic figure Lord Krishna. It consists of a cylindrical tube closed at one end. The westerners have both metal and wooden flutes. Silver and gold are among the metals used while crocus-wood and ebonite are employed in the construction of flutes intended for orchestral music. In India it is usually made from bamboo though teak-wood and cane may also be used. In all these instruments there is a hole in the side near the closed end known as the "mouth-hole". In addition to this there are other lateral holes in it. In western instruments the mouth-hole and the other holes are usually of the same size while in Indian flutes the mouth-hole is bigger in size than the other holes. The number of lateral holes varies from instrument to instrument. The South Indian flute usually contains eight finger holes. But the talented flutist Sri Sanjeevi Rao uses one containing nine finger holes. Though six holes are the bare minimum required additional holes have been found necessary in practice for good rendering of music.

While playing, the instrument is held traversely with the mouth-hole slightly turned outwards with the lower lip of the performer resting on the near edge of the hole. A blade-shaped column of air is then blown across the edge of the mouth-hole for the production of the sound. This column of air and the one inside the cylindrical pipe together comprise the vibrating system while the manipulative mechanism for the production of the notes of the scale consists in regulating the effective length of the tube in use by covering the lateral holes wholly or partially with the fingers. When all the holes are closed the flute gives the note of an open pipe whose length is the distance between the mouth-hole and the open end. Helmholtz was the first scientist to explain the production of sound and its maintenance in this instrument.

Fig. 10
The Flute

.His explanation consists in regarding the blade-shaped column of air coming from the mouth of the player as a sort of reed vibrating under the action of the air column in the tube. The vibration of the air inside the tube causes the air reed alternately to enter or pass over the mouth-hole. That is during a condensation inside the pipe the blade-shaped column is sucked in and during a rarefaction the blade is thrown out. But Helmholtz has not been

able to explain satisfactorily how the vibration starts in the air column of the tube. This explanation has been superseded by the modern researches of E. G. Richardson and others. They explain the working of the flute on the basis of the vortex motion and "edge tones." The phenomena of edge tones bear a resemblance to "Aeolian tones", a familiar example of which is the singing of the telegraph wires. When a stick is held vertically in a flowing stream of water the formation of eddies on either side of the stick with its cores parallel to it can be observed. These vortices will be found to revolve in opposite directions which will soon be detached and carried along with the stream. A periodic push and pull will be experi-

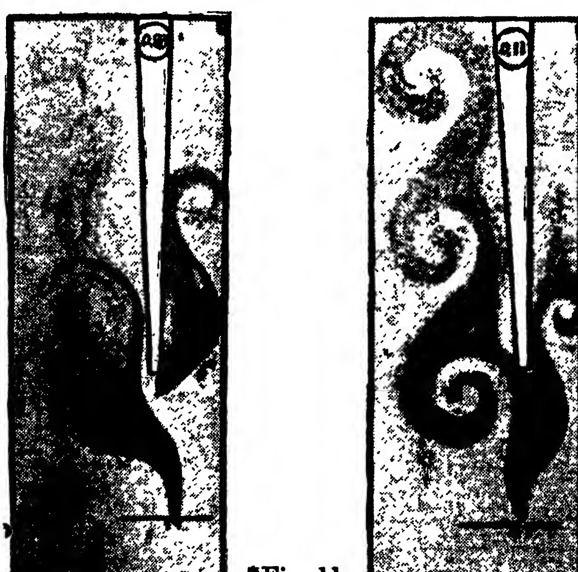


Fig. 11

Separation of vortices in edge-tones.

enced by the stick in a direction at right angles to the stream making it vibrate transversely. The

same phenomenon happens when the obstacle is moving in a stationary fluid. If the frequency of the eddies when they are formed past a wire in an air stream coincides with one of the natural frequencies of the wire an "Aeolian tone" is produced. The "edge tone" which resembles the "Aeolian tone" is produced when a blade-shaped column of air from a slit strikes a sharp edge of an obstacle. This is what happens at the mouth-hole of the flute. It has been found that the "edge tone" rises in pitch with the pressure of the air that is blown. But in the flute the air column inside limits the pitch of the "edge tone" to its natural series. For instance, if the blowing pressure is continually increased though the frequency of the "edge tone" increases along with it, things settle only when the octave of the pipe is heard. Thus the note of the flute jumps an octave.

To regard the flute as an open pipe will not be sufficient to explain some of the details observed in the playing of this instrument. As a matter of fact even in its construction it can be noticed that the lateral holes are not arranged from the mouth-hole at distances corresponding to the frequencies of the notes produced in an open pipe. To a certain extent it can also be considered as an "Helmholtz resonator." In this class of resonators the opening to the external air is very small in comparison with the enclosed cavity. It is known that in this resonator the pitch can be raised by enlarging the opening. This fact is used by the flutist while playing. Uncovering the holes is equivalent to enlarging the opening of the resonator and the larger a hole is, the greater is its effect in raising

the pitch. It can also be understood now why when first the holes are made, if the instrument does not give a true scale, the holes are altered in size to correct the errors. It was formerly regarded that the resonant conditions of the pipe and Helmholtz resonators were entirely different. Recently E. G. Richardson has given a method based on acoustic impedence which results in a complete reconciliation of both the types.

The quality of the note produced is affected to a certain extent by the material of which the flute is made and by the bore of the pipe. It has been shown by Helmholtz that the quality depends on the overtones in the note produced. Theoretically small bore pipes will have a large retinue of upper partials while wide pipes will have fewer upper partials. Helmholtz has found that the flute notes contain very few and feeble overtones. Later work on the acoustic spectrum of the flute notes has also confirmed this. He attributes the soft and smooth quality of flute notes as contrasted with those of violin and reed instruments to this fact. He also attributes the less penetrating tonal quality of the wooden flutes compared to the metal ones to the more yielding properties of the wooden sides. The capabilities of this instrument are unlimited in the hands of an expert player for obtaining sustained notes, leaps, turns, shakes etc. Especially the use of the finger strokes by our gifted flutists in playing Madhyama kala and trikala sangatis in Carnatic music is marvellous.

CHAPTER VII

REED INSTRUMENTS

Reed instruments are very common both among us and in the west. They are the important instruments in the western orchestra. It is a well-known fact that in South India the Nadhaswaram holds a unique place in all our religious and social festivities. It is the best among the indigenous reed instruments. Every temple has got a piper attached to it and no marriage is celebrated without Nadhaswaram music. Reed instruments as a class are famous for their voluminous and resonant sound. In some instruments metal reeds are used either with pipes or without pipes. The reed organ pipe is a metal reed instrument with pipes while the harmonium is a metal reed instrument without pipes. Besides metal reeds cane reeds are also employed. Both single and double cane reeds are used. The clarinet is an example of a single cane reed instrument. Oboe and our Nadhaswaram are examples of a double cane reed instrument. A study of the acoustics of all these reed instruments reveals interesting details about their construction and tonal qualities. We shall consider a few typical instruments among them.

The reed of a harmonium is a metal strip screwed down tightly at one end to a metal block. It is so shaped as to fit into an aperture made in

that block. During its vibration the strip swings into the aperture and out of it with a small amount of clearance space. This reed lies between two

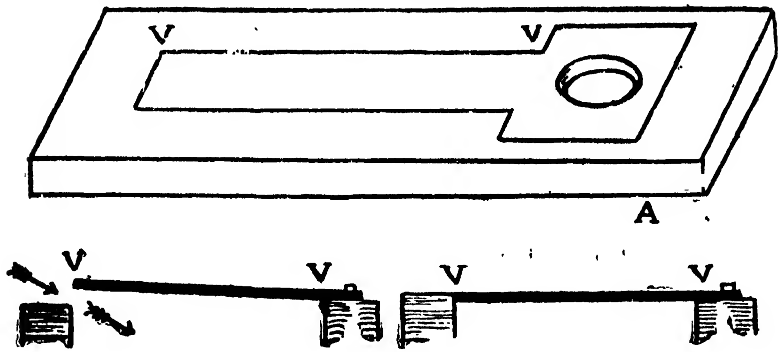


Fig. 12
The harmonium reed.

wind chests and when the appropriate stop of the harmonium is drawn air rushes from the lower to the upper wind chest setting the reed in vibration. The stream of air is then reduced into a series of separate puffs because the reed alternately opens and closes the aperture. A sound is then generated with a frequency equal to that of the free vibration of the reed. The pressure of the alternating puffs of air has very little influence on these stiff and rather heavy reeds and hence they vibrate with their natural frequencies. As there are no pipes to modify its very high upper partials its sound retains the cutting character. For every note in the musical scale a reed has been provided in the instrument. The construction of the reed organ pipe is different. Its reed differs from that of the harmonium. This is purposely made to be too large to fit into the aperture. Hence it does not swing in and out of the aperture but strikes against it at intervals. A pipe of appropriate length and

shape is added to reinforce the vibration of the reed. It is this resonating pipe which makes the

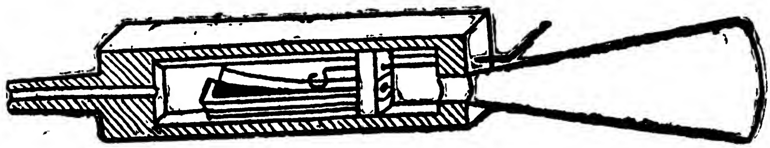


Fig. 13
The reed pipe with sound horn.

tonal quality of the organ pipe different from that of the harmonium. A striking reed is used in preference to a free reed, in order to have plenty of higher harmonics. It is these higher harmonics that account for the brilliance of the organ sound. Now a days the reeds are curved at their ends so that they can come down with a rolling motion and gradually cover the aperture. They make the higher harmonics less prominent and hence make the tone more pleasing. Each reed is coupled to a resonator. The shapes of these resonators vary. Both cylindrical pipes and conical pipes are used while in some cases the pipes are short cones surmounted by cylinders. To make slight alterations in the pitch of the reed a wire is provided to press the reed near its root and by moving it the reed can be made a little longer or a little shorter. It is claimed that it is possible to imitate all the tonal qualities of the numerous instruments in the western orchestra by varying the make of the reeds and the shape of the pipes coupled to them.

The clarinet is a single cane reed instrument with a pipe attached to it. This is a very ancient instrument. It occupies a unique place in the western orchestra and military bands. Clarinets

are made for a variety of pitches. The single reed lies over an opening in a mouth piece which is so shaped so as to fit readily between the player's lips. It is secured to the mouth piece by two ligatures. It is tapered in thickness from the ligature to the beak. The air from the player's mouth operates the reed and sets it in vibration. It vibrates in the same way as the striking reed in the organ pipe. The pipe attached to the reed in this instrument consists of a cylindrical tube in three sections with a small bell-mouth. This pipe is made either in silver or wood. A number of holes are made in its side and keys are provided for operating these holes. When all the finger-holes are covered the complete column of air is in use and the clarinet sounds its lowest note. For playing the different notes the length of the air column is altered with the help of the keys. The cane reed being very much lighter than metal reeds is easily forced to vibrate with frequencies quite different from those natural to it. The production of sound in this instrument can be explained in this way. The reed and the air column in the pipe form a coupled system. This system is maintained in vibration by the wind from the player's mouth. The pressure of the air entering is controlled by the player by his cheeks while playing.

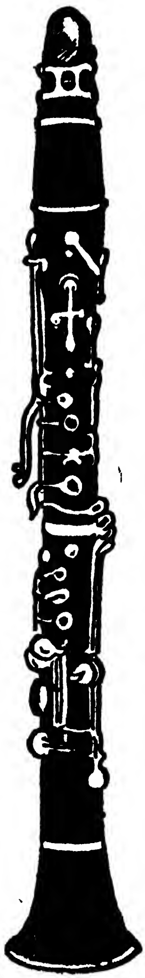


Fig. 14
The Clarinet.

The vibration of the reed varies the rate at which air enters the pipe. The stream of air being thus reduced to a series of puffs sets the air column in the pipe in vibration. The varying pressure associated with this vibration in the pipe reacts on the reed and forces it to assume a frequency natural to the column of air in the pipe. It thus behaves unlike the reeds of harmoniums anp the pipe organ.

The action of a double reed instrument is slightly different. The two reeds are bound together at their roots leaving an orifice at their free ends. After inserting this piece into the conical pipe the player holds it in his mouth and blows air into it. The reeds then beat against each other and vibrate. They alternately open and close the aperture. The varying pressure is communicated to the column of air in the pipe. In these instruments conical pipes are used instead of cylindrical pipes. The air column also vibrates and the pitch of the resulting sound is determined by the air column. The coupling between the reed and the pipe must be tight, otherwise the reed will escape from its bondage and vibrate with its natural frequency. The "quack" heard sometimes when an unskilful player plays on the Nadhaswaram is due to the natural vibration of the reed. The conical pipe is provided with side

Fig. 15
The Oboe.

holes. In the case of the oboe there are keys to operate the holes. Different notes are played by covering these sideholes appropriately. The pipe in the Nadhaswaram will be from two to two and a half feet long. The longer the pipe the lower will be its 'sruti' or starting point in the musical scale. The pipe is made either in wood or metal. Silver and gold are the metals usually chosen. If wood is employed a close grained wood is preferred. In South India "Acha" wood is taken. The pipe usually contains twelve side holes eight in one line and the remaining four being distributed on both sides of this line near the bottom. Only seven holes are used for fingering. The others are intended to regulate the pitch of the instrument.

The tonal qualities of these reed instruments depend upon a number of factors. The air column, the material and shape of the pipe are the major factors controlling the quality. Since the clarinet pipe is cylindrical with one end closed the tones possibly form an odd harmonic series. In the case of oboe and Nadhaswaram the possible tones form a full harmonic series as their pipes are conical. This difference in shape of the pipes of the clarinet and oboe is mainly responsible for the difference in the tonal qualities of the clarinet family and oboe family. If the clarinet is over-blown the first over-tone obtained is the twelfth above the prime and not the octave as in the case of oboe and Nadhaswaram. Hence a sufficient number of side holes and keys must be provided in the clarinet to bridge this gap. The

bell-shaped end is the next important factor. Its influence diminishes when several of the lower note holes are open. The widening out of the pipe at the bell-end has been found to introduce even partials to a certain extent which are absent in the case of clarinet and to reinforce them in the case of Nadhaswaram and oboe. It has also been found to reduce the intensity of the higher partial tones. The more important influence is that it helps to radiate the sound more efficiently in the atmosphere. The way in which the material of the pipe affects the tonal quality is not yet completely understood. Though theoretically the air column and the reed alone form the vibrating system, experiment has shown that if the walls of the pipe are sound-absorbent there is a slight lowering of pitch as compared with a rigid wall. More than this effect the tone is made weak and heavily damped if the walls are sound-absorbent. Much of the energy of the player is used up in setting up vibration in the walls instead of the column of air. So efficiency in the production of sound goes with metal pipes rather than with wooden pipes. It has also been found that the more rigid the walls the greater is the possibility of the pipe having marked natural frequencies. This leads to an enhancement of notes in certain regions of the scale and thus the quality is affected. Nadhaswaram seems to have no parallel to it in its tonal quality among the indigenous instruments. It possesses a highly pleasing and rich sound. It can be heard distinctly even at a great distance. It is

said that Carnatic music owes not a little to this instrument for its preservation. Ragas, the peculiar feature of the Carnatic music, can be played for hours together on this instrument without becoming stale. Its influence on other kinds of instrumental music and vocal music has become considerable in recent times. Above all it is the only indigenous instrument that fills the ears of large masses of people with high class music.

CHAPTER VIII

THE MRIDANGA

All drums belong to the class of percussion instruments; their popularity among all nations from very ancient times is a well established fact. Among the infinite variety of drums now in use among us, the mridanga is certainly the best and the most ancient. In Western music drums play only a secondary part; they are mere rhythm markers. Even in India the North-Indian drums are used only for that purpose. But any one who has listened to a Carnatic concert can recognise the importance of mridanga. The mridanga player has to produce appropriate accompanying sounds when the vocalist sings svarams or sangatis in

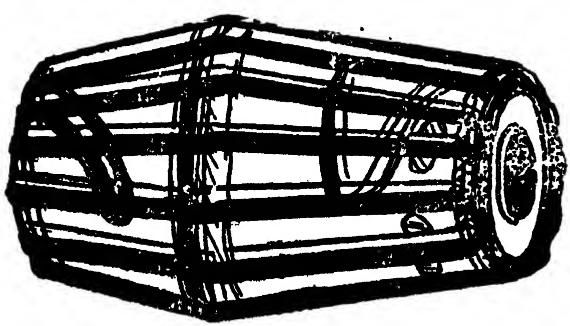


Fig. 16
The Mridanga.

kirtanams to enhance the musical effect. This onerous task is admirably performed by expert players. The late Narayanaswami Appa of Tanjore and Alaganambi Pillai of Kumbakonam in recent times and Palghat Mani to-day, have shown the

immense possibilities of this unique instrument. Scientifically the use of membranes as vibrators in musical instruments is to be viewed with disfavour because of their inharmonic series of overtones. To have made these membranes yield harmonic overtones and to have successfully employed them in their musical drums bear sufficient testimony to the musical genius of the Indian people.

In all these instruments the membrane is usually stretched either on a shallow frame or a cavity. The membrane is set in vibration either by direct percussion of the hand or with a stick. A circular membrane alone is used in preference to other shapes. The mathematical treatment of such circular membranes has been fully discussed by Lord Rayleigh. In that discussion the membrane is taken as a perfectly flexible and infinitely thin lamina of matter. It is again supposed to be of uniform material and thickness. The discussion of even such an ideal membrane is of a very complex nature. In actual practice many deviations occur which are not allowed for in the theory. For instance, in the drum the tension is not the only restoring force. The membrane as it vibrates alternately compresses and expands the air in the cavity. This reacts on the membrane and changes its natural frequencies. Further the drums are not only struck at the centre but also at other

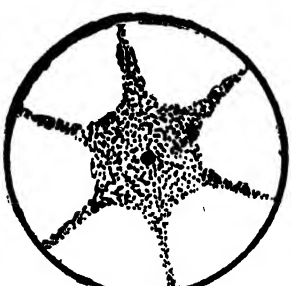


Fig. 17
Chladni's figures.

points between the centre and the edge. The modes of vibration in a drum can be studied in a general way by the well-known Chladni's device of strewing fine sand on the membrane. The sand tends to collect in the still places known as the nodal lines. The shape of a few such lines pertaining to a circular membrane can be seen in the illustration.

The mridanga consists of a hollow shell made usually of Jackwood. In shape it resembles a barrel and is about two feet long. Drums with lesser lengths were popular some twenty years ago. Moreover it is not of the same diameter from one end to the other. It has a bulge about the middle but nearer the left and which has a larger disc than the right. The two skin-heads are stretched over the ends in an elaborate way. The construction of the right head differs slightly from the left. The right head consists of three layers of skin; the first and third are in the form of rings while the middle one is a complete disc. The rings are made of goat's skin while the disc is of cow's skin. Before tightening the head the pieces are kept in a wet condition for a long time. Three leather braces are interlaced and they are passed round the head through holes made along the circumference of the skins which fit round the head as a hoop. This hoop is pulled down from different points on its circumference to the other head by long leather braces passing many times along the length of the drum. The left skin-head consists of two layers; one is in the form of a ring while the other is a full

circular piece. Buffalo's skin is used for the ring while goat's skin is used for the circular bit; small pieces of wood are inserted between the shell and the braces for altering the tension still further. To the centre of the right skinhead is applied a paste consisting of resin, boiled rice and fine dust. This is spread uniformly and the quantity is increased till the sounds obtained by striking the head at its middle and the edge agree in pitch. These sounds are known as "chapu" and "meetu" in musical parlance. The paste on becoming dry adheres to it permanently and is of shining black colour. When the instrument is about to be played a mixture of flour and water is applied to the centre of the left head and this plaster is removed carefully after each performance. This helps to elicit the dull sound "Panchama" from it. The note of the right head is "Sa" and is elicited by playing with the fingers of the right hand which strike it either at the edge or in the centre.

As has been pointed out earlier the partials of an unloaded circular membrane form an inharmonic series. The peculiarity of the Indian drums is that they are loaded over a central zone in such a way as to give harmonic partials. It has been theoretically established that if the weight or thickness of the skin is increased progressively from rim to centre the overtones would become harmonic. This fact has been used empirically by the makers of the Indian drums from a very early period to secure the above result. The cylindrical chamber has also been found to have a profound effect in

improving the volume and quality of the tone; but with a slight crack in the walls of the wooden shell, the tone becomes dull and loses its quality. The technique of drumming is very elaborate. The instrument is played by the hands, finger tips and wrists in a peculiar manner which can be acquired only after considerable practice. It was Sir C. V. Raman and Professor R. N. Ghosh who were mainly responsible for bringing the remarkable features of these drums to the notice of western scientists.

CHAPTER IX

BELLS

The vibrations of solid structures such as cymbals and bells have been utilised for a variety of purposes from time immemorial. Both are percussion instruments. In the case of bells there are air cavities to reinforce the plate vibrations while they are absent in cymbals. The history of bells is full of romantic interest. In all countries they have been used for both religious and secular purposes. The temple bell and the church bell have always remained indispensable for summoning the devotees to places of worship. It was a custom in olden days to use the bells to rally the soldiers at a moment's notice in cases of urgent need. Hence came the saying "He who commanded the bell commanded the town." In South India there is an interesting story current about the bell. It is said that King Manu Needi Chola during his reign issued a proclamation that whoever had a grievance was at liberty to bring it to his notice by ringing the bell in his palace at any time. It seems one day a cow was found to ring the bell. The king on hearing the sound made an enquiry and learnt that its calf had just then been killed by the chariot of his own son. It is said he immediately issued an order to kill his son at the same place by driving the same chariot over him.

The use of bells for purposes of music is very limited. It is true that they emit a pleasing note. Besides satisfying the necessary requisites for

producing and sustaining the vibrations, a musical instrument should possess the most important requisite of a manipulative mechanism for rapidly playing the notes according to a musical scale The construction of this manipulative mechanism is rather difficult in the case of bells; because of their size and other factors relating to the production and regulation of their sounds. Still both carillons and chimes have been in use for a very long time. They refer to a set of bells tuned to a musical scale. The chimes are more widely known as they are always found in big tower clocks. The clock mechanism controls the ringing of these bells. This is done by a system of wires connected to small hammers. There is a revolving barrel set with studs as touch pieces at the required points which actuate the levers attached to the hammers. The hammers then strike the bells at definite intervals. The carillon on the other hand is a very elaborate piece of machinery. There will be at least two complete octaves of bells in it. Carillons having four octaves are also in use. The carillons of Belgium and Holland containing more than fortyfive bells are world famous. These are struck by clappers operated by electro-magnets. In an orchestra the bell is also used for its sonorous timbre. Nowadays they use a set of metal tubes known as tubephone to imitate the bell timbre. This consists of a number of metal tubes supported on a frame and are struck by a hammer. Tubes of different lengths and thickness are taken for the different notes in the octave. Bars of metal and wood are also employed. These are known as xylophones.

We also employ the vibrations of solid structures in our music. The different varieties of metal cymbals known as Jalara, another instrument known as Chittika and Jalatarang may be mentioned as examples. The Jalara consists of two circular plates each sunk at its centre. By striking one against the other in a peculiar way a ringing sound can be produced. There is another variety in common use which is cup-shaped. While playing this, one of them will be held tightly in the left hand and the other held loosely in the right hand will be made to strike it. Many modulations of tone are produced by expert players in this type of cymbal. Similar to this is the instrument known as Chittika which is used in Harikatha Kalakshepams. This consists of two pieces of hard wood which are flat on one side and rounded on the other. They contain clusters of small bells at their ends which make a jingling sound when the flat surfaces are beaten together. For playing, the thumb and the fingers in the right hand are passed through the rings fixed at the back of each piece and the flat surfaces are beaten together by alternately closing and opening the fingers. These instruments just described are only used to enhance the rhythmic effect. They cannot be called regular musical instruments. But Jalatarang is a regular musical instrument. This consists of a series of porcelain cups big and small. They are all filled with different quantities of water and are struck with sticks. The notes are played according to the musical scale.

The study of the vibrations of these solid structures bristles with a number of difficulties

The simplest solid structure is a plate of uniform thickness. The experimental study of the vibrations of such plates started by Chladni is more helpful than the theoretical study. By the simple expedient of sprinkling fine sand on the surface of a plate fixed at its middle point, Chladni demonstrated the different modes of its vibration by bowing at its edge. The sand then makes a pattern on the plate. The form of the pattern was found to alter by changing the place at which it is fixed and also the place at which it is bowed. These patterns are called Chladni figures. The formation of these patterns can be easily understood. It is well-known that string can be made to vibrate in any number of separate sections or segments. In the same way a plate can be made to vibrate in a number of separate portions. The point of rest on the string becomes a line of rest on the plate. The sand sprinkled on it moves on till it settles on these lines of rest. These lines of rest are known as Nodal lines. Each different sand pattern shows a different mode of vibration corresponding to a different note given out by the plate. If the plate is bowed or struck without an attempt to control the mode of vibration the result will be a confused pattern on the plate. The sound then heard will be very harsh. To facilitate the formation of these patterns it is usual to touch the plate lightly at one or two points while it is being bowed. The more complicated the pattern the higher will be the corresponding note. It has been shown by Helmholtz that the timbre of a note depends upon the overtones contained in it. The number and strength of these overtones is settled by the mode of

vibration. In the case of plates the overtones are generally inharmonic with one another and that is the reason for their unpleasant effect on our ears. This theory is applicable to cymbals and bells because they can be regarded as curved plates. The art of the bell-founder consists in designing it in such a way as to make the bell note sweet by making its overtones harmonic.

There is an infinite variety of bells with numerous shapes. To realise this variety one has only to think of bells such as hand bells, electric bells, calling bells, cycle bells, cow bells and a host of others. The forms in many cases are approximately cylindrical or conical or hemispherical. For casting the bell an alloy known as bell-metal is used. It contains copper and tin in the proportion of four to one; zinc and lead are also used in small bells. It will be noticed that the shape of the large bells used in temples and churches is rather peculiar. Its cross-section and thickness will not be uniform throughout. Halfway down the bell is the " waist " and the lower end is known as the " lip " or " brim." Near the lower end where the shape curves outward is the striking place of the clapper. This is known as the " sound-bow." At this place the inside and outwide sections will have opposite curvatures. The thickness at the sound-bow will range from one-twelfth to one-fifteenth of its diameter. The blow of the clapper sets the bell in vibration. The nodal lines formed then may be divided into two classes, one running up and down the bell, and the other around it. It is customary to speak of these classes as nodal meridians and nodal circles. Lord Rayleigh

examined a number of church bells and found out experimentally the various over-tones. He found for the fundamental tone four sectors, for the octave four sectors and a ring, for the octave and minor third six sectors, for the twelfth sixth sectors and a ring, for the double octave eight sectors and so on. The interval relations of the overtones given above by him are only approximate. It is the bell-founder who by adjusting the thickness at various sections makes these tones as nearly harmonic as possible with one another. Besides these overtones which can be elicited by resonance, another tone was noticed which immediatly after striking over-powers all the other overtones. This is known as the "striking note." It has not been found possible to elicit this by resonance and hence it is considered to be an aural illusion. The bell founder names the bell by the pitch of this striking note. It seems to be near that of the second overtone, that is the octave. The fundamental pitch of the bell depends on the internal diameter; the greater this is, the lower will be the note. To tune the bell, the bell is placed in an inverted position below a machine with a rotating cutting tool and metal is removed from the right place inside the bell. The note heard from a bell will often be accompanied by beats. If the bell is not perfectly symmetrical about its axis two normal modes are simultaneously set up which give rise to these beats. The same phenomenon is noticed in the case of cymbals also. It may be asked why Fourier method cannot be applied to the sounds from bells for their analysis. This is not possible because the curves which can be obtained for the bell sounds will be non-periodic

with no apparent wavelength. An analysis by the Fourier method will only lead to an infinite number of components, while the real sound is undoubtedly compounded from a finite number of partials which are only very nearly harmonic. In conclusion it has to be admitted that the art of bell-casting continues to be a mystery.

CHAPTER X

MELODY

Music is the oldest among the Fine Arts. Its wide appeal to mankind has been recognised from earliest times. It has borne a close relation to religion in all countries. Without music religion would lose one half of its power. In social life also it has held a high place in every nation. "The aim of music is to weave the elementary sounds into sequences and combinations which give pleasure to the brain through the ear." Besides it has got an educational value in disciplining the human mind. "Gymnastics for the body, music for the mind" is commonly heard in educational parlance.

The three elements of music are Melody Harmony and Rhythm. A collection of notes played in succession constitutes melody. When they are played in succession a unity is perceived among them which gives us pleasure by awakening our musical imagination. (If the notes are played simultaneously, harmony arises. From the effect of these superimposed sounds we derive pleasure. The sound patterns produced in our minds by the single notes played in melodic succession and by a series of notes played simultaneously are entirely different. Rhythm regulates the playing of these notes. Of the three elements of music rhythm must be accorded the honour of antiquity. Primitive music has been predominantly rhythmical.)

Musical notes are produced by regular vibrations such as those of strings or gas columns. The more rapid the vibration the higher is the pitch of the note. The rate of vibration which determines the pitch of a note is also referred to by the term "frequency." The relation between any two notes is called the musical interval between them. A musical interval can be expressed in a number of ways. For example, if we táke two notes which vibrate 256 and 512 times a second respectively, the physicist would express the musical interval between them as 2. The musician would call this interval an octove. The other common intervals termed as the fifth, fourth, Major Third, Minor Third, Major Sixth and Minor Sixth by the musician denote the ratios, 3/2, 4/3, 5/4, 6/5, 5/3 and 8/5 respectively. The width of a musical interval is also expressed either in cents or savarts. This is more convenient for this reason. Suppose we have to add the intervals of a fifth and a fourth. We really do that by multiplying the corresponding ratios and similarly when subtracting one interval from another, we really divide the corresponding ratios. This calculation is conveniently made with the help of logarithmic tables. The basis of this calculation is simple. The interval ratio 2 for the octave is taken to be equal to 1200 cents. The number of cents for any other interval is obtained by multiplying the logarithm of its frequency ratio by a conversion factor of value 3986. Some find this factor inconvenient and use 1000 instead in which case the octave has to be divided into 300 parts. Each part is called a "Savarat."

The alterations of pitch in melodies take place by intervals which are regulated by some kind of rhythmic arrangement. These intervals form the musical scale in which the melody moves. In selecting the particular intervals for the musical scale national differences of taste have played a large part. Moreover different nations have answered differently the question of the smallest interval that is admissable in a scale. It seems that in the first stages of development of musical scales many nations avoided the use of intervals of less than 9/8. It is said that scales of this kind are still found among the Chinese and Malays of Java and Sumatra. We can conjecture how the present day musical scales must have come into existence. The octave interval is fundamental in music of all ages and of all countries. This must have been discovered first. Later on the interval of a Fifth, and its inversion the Fourth must have been recognised. Thus the four notes C, F, G, C, must have constituted the earliest scale. Then they must have tried the fifth from G and added D to the collection. Repeating it A must have been added. In course of time, other smaller intervals must have come into vogue. European nations have followed the Greek system and have retained the semi-tone interval of frequency ratio 16/15 as the limit. Pythogoras is said to have been the first to establish the eight complete degrees of the Diatonic Scale (C/264, D/297, E/330, F/352, G/396, A/440, B/495, C'/528) containing three different intervals of 9/8, 10/9 and 16/15. With the growth of instrumental music, Tempered scale came into existence. What these scales are can be understood

from the following illustration. Suppose we have a keyed instrument containing a certain number of octaves each divided into seven notes forming the Diatonic Major Scale. The major scale can be played only with C as the tonic. If we want to play in a key other than that of C, we have to introduce notes which are not in the original key. This number becomes very large if we take all the seven notes one after the other as the key. Introduction of this large number of notes makes the instrument unwieldy. For the sake of convenience perfect tuning was given up. Expedients which are made for the sake of convenience are known as systems of Temperament. Of these, two alone have had extended use *viz.* Mean Tone Temperament and Equal Temperament. In the Meantone Temperament the major thirds are kept pure, and the note which lies between the notes of each major third is put half way between them. The Equal Temperament is the most convenient and popular one. In this the octave is divided into twelve equal parts. Two of these parts are taken for a whole step and one for a half step. Thus each whole step is 200 cents and each half step is 100 cents. Advocates have not been wanting both for and against this system. In any tempered scale the purity of the intervals is sacrificed and in the equally tempered scale though the important intervals of the fourth and fifth do not suffer appreciably the other intervals do suffer from the compromise. It is said that these deficiencies are concealed to a great extent because of the rapid movement in the instrumental music. However when notes are jumped in the shape of chords, these small differences of pitch

greatly diminish the significance of the chords. The most telling argument against its use is this. It is an accepted fact that the more simple the ratios between sounds the more harmonious is their relation and the more complicated the ratios the more dissonant are the sounds. Temperament is musically absurd because it replaces the simple ratios of the notes by ratios which are nearer to them but nevertheless extremely complicated. In spite of this it is claimed by westerners that the high development of their instrumental music would not have been possible but for Temperament.

In India apart from acoustical principles tradition has played a considerable part in the development of musical scales. The Saman chant is the earliest example of our musical scale. In evolving scales there is ample evidence to show that our ancients were fully aware of many of the acoustic principles. For example, the phenomenon of consonance and dissonance which is the fundamental principle of Harmonic music was known to them. Samvaditva is consonance. They were aware of the significance of overtones long before Helmholtz discovered them for western musicians. One remarkable feature in the development of our scales is the various intervals they have tried and fixed. The smallest interval which they denote as struti has been a varying unit. The intervals of major tone (9/8), minor tone (10/9) and semi-tone (16/15) have been taken by them to be equal to four strutis, three strutis and two strutis respectively. That these strutis are not of equal value can be shown by a simple calculation. It can also be shown in a number of ways that they have taken the octave to consist of twenty-two strutis. To give one

example let us suppose we proceed to form the eight degrees of the octave by a succession of fifths in which case it can be shown that there are five major tone intervals of ratio 9/8, two intervals of 256/243. Each of the latter is termed by them as a struti. For the five major tone intervals there will be twenty strutis and hence the octave will contain twenty-two strutis. A symbolic necessity for dividing the octave into twenty-two strutis is also pointed out by one writer. The number 22 is related to 7 by the ratio 22/7 which expresses the relation between the circumference and diameter of a circle which is considered as the most perfect shape. Though the octave is taken to consist of twenty-two steps at a time only a limited number of notes is played for a melody. This we term a Raga. We have inherited a remarkable system employing a vast number of these scales capable of representing all shades of feeling. A systematic classification of these scales for the first time was done by Venkatamakhin. His system is the most scientific system that can be related to our present day Carnatic Music. In his method, though he divides the octave into sixteen divisions, he takes it really to consist of twelve divisions. With that he builds up his seventy-two primary scales and innumerable secondary scales. Though an infinite number of scales are mathematically possible from his calculations only a certain number has been found musically acceptable. The three famous South Indian composers Tyagaraja, Dikshatar and Syama Sastri had employed many of the scales listed by Venkatamakhin. It is for the present day musicians to bring many more of his scales into prominence and thus enrich our musical heritage.

Chapter XI

HARMONY

Indian music has been built on Melody and European music on Harmony. In both the systems one particular note is always taken as the central point. This is called the tonic to which all the succeeding notes are related. In the melodic system the relation between the tonic and the succeeding notes is found by the work of memory. But in the harmonic system as the notes are played simultaneously their relation to the tone is directly felt. When voices and instruments move forward in an orchestra their notes must form consonances with one another. If they are dissonant the music will be spoiled. To attain perfection in the music played the co-operation of all parts is very essential. To secure this we must consider not only the relations of the notes in the piece of music with its tonic but also of its chords with its Tonic chord. When these relations are properly adjusted harmony becomes perfect. The physical side of harmony has been well understood by scientists.

Sounds are caused by vibrations. The number of vibrations made per second is termed "frequency." On this depends the pitch of the sound. The greater the frequency the higher is the pitch. Almost all the sounds we hear are composite. The human ear is able to perceive pendular vibrations alone as simple tones. It has been shown that all varieties of sound are due to particular combinations of a smaller or larger number of simple tones. These

separate component tones in the composite sound are called partials. The partial having the lowest frequency is called the fundamental while the others are called overtones. If the overtones have frequencies which are multiples of the fundamental they are termed harmonics. Otherwise they are known as inharmonics.

If two simple tones of nearly the same frequency are sounded at the same time, we do not hear them as two tones. We hear only one tone of which the frequency lies between the frequencies of the components and of which the loudness increases and decreases periodically. This periodic waxing and waning of the resultant sound is known as beats. Beats are counted from the instant when the resultant sound is loudest to the next instant when it is again loudest. They can also be counted from the instant when the resultant sound is faintest to the next instant when it is again faintest. The frequency with which the beats occur can be shown to be equal to the difference between the frequencies of the components. When there are more than two tones having nearly the same frequencies beats can occur in a number of ways.

When two simple tones whose frequencies are p and q and which are well separated from one another reach the ear at the same time, a third tone of frequency $p-q$ is heard along with the components. Among the musicians who were the first to observe this difference tone was the famous Italian violinist Tartini. In honour of him this tone is also called Tartini's tone. It is a very common occurrence and many practical uses are

made of this difference tone. The policeman's whistle is an example. When a blast of air is blown into the whistle it is distributed equally over the mouths of the two pipes of unequal length. The difference tone is then heard loudly. Helmholtz showed that there is likewise produced a tone of frequency $p+q$ which he called the summation tone. This is much more difficult to hear than the difference tone and that is why it escaped notice at first. These two go under the name of combination tones. The cause of this phenomenon was not properly understood until Helmholtz investigated it. In Harmonic music when a whole lot of simple tones of frequencies p, q, r etc., are sounded simultaneously all their difference tones of frequencies, $p-q$, $q-r$, $p-r$ are heard along with $p+q$, $q+r$ and $p+r$. These are known as combination tones of the first order. There are other orders as well. For instance a first order difference tone may combine with one of the generating tones to give a difference tone of the second order, a second order difference tone may combine with one of the generating tones or one of the first order difference tones to give a difference tone of the third order and so on. Similarly for summational tones. These combination tones must be taken into account along with overtones for deciding the consonance and dissonance.

It was recognised long ago that certain combinations of tones when produced together give rise to a pleasing effect and some other combinations produce a decidedly harsh effect on the ears. This pleasing effect is known as consonance and the harsh effect is known as dissonance. When con-

sonance was produced it was found that the ratio of the frequencies of the two tones was a small number. The smaller the number the better is the consonance. It was Pythogoras who first began to investigate the reasons for consonance and dissonance. Everything is Number and Harmony was the principle of his doctrine. After him Euler attempted an explanation of the phenomenon. He said that the human mind always delights in law and order and that it always tries to discover the same in Nature also. According to him it is only when two tones have frequencies which can be expressed in small numbers that the mind takes a delight in hearing them. The first scientist who tried to give an explanation on a physical basis was D'Alembert. Finally it was Helmholtz who developed a complete theory of consonance and dissonance. His theory in bare outline is this: He found that all dissonances are due to unpleasant beats generated by component tones and that consonances are formed by tones which fail to produce such beats. We will consider the theory in detail now.

We have already seen that, when the frequencies of two tones are very nearly the same, beats are produced. These beats will be slow when the difference in frequency is small. But as it becomes larger the beats will grow more rapid. When they are moderately slow the effect may be pleasing but when they are rapid the effect is decidedly unpleasant. If they become still more rapid the unpleasantness decreases and when they reach a limit the ear is no longer able to detect them at all. A similar phenomenon is noticed in the case of our eyes also. Suppose we look at a light which varies

periodically in brightness. When the variations in brightness become moderately rapid the flickering effect becomes decidedly unpleasant, but as the variations grow still faster the unpleasant effect decreases and when the variations become sufficiently rapid the flickering blends into what looks to the eye like a steady light.

After establishing this fact that annoyance is always caused by intermittent stimuli, Helmholtz found out the circumstances under which such unpleasant beats arise in the various combinations of tones through either the partial or combinational tones. First he examined the conditions necessary for the production of dissonance between two simple tones. His conclusions can be better understood by taking an example. As sources for the two simple tones let us take a pair of middle C (264) tuning forks. By attaching wax to one of the prongs of one fork we can lower its frequency and study the beats when they are sounded together. It will be seen that the roughness due to their beats reaches its maximum when the interval between them is about a half-tone. On increasing the interval still further it will become less marked and when the interval amounts to a minor third roughness altogether ceases. From this it can be understood that dissonance arises between two simple tones when they form with each other an interval less than a minor third. This interval is called the beating distance for the two tones. It will also be clear that the same beating interval will give rise to very different numbers of beats per second according as the tones occupy a low or high position in the scale. Next

we shall consider the consonance and dissonance of a composite tone. We have already seen that in it there will be a number of partial tones. Up to the seventh overtone the partials are out of beating distance. Above the seventh they close in rapidly upon each other. These will produce harsh dissonances with each other. Helmholtz says that this is the reason for the harsh character of trumpet notes. So it can be concluded that the partial tone series above the seventh when present will merely contribute noise to the composite tone. Next we shall consider the consonance and dissonance produced when two composite tones are sounded together. Dissonance due to beats will be produced if a partial tone belonging to one composite tone is within beating distance of a partial tone belonging to the other composite tone. Several pairs of tones may be thus situated and if so each will contribute its share of unpleasantness to the general effect. The unpleasantness of any pair will depend chiefly on the respective orders to which the beating partial tones belong and on the interval between them. Thus in determining the general effect of a combination of two composite tones we have to ascertain what pairs of partials come within beating distance and also to estimate the amount of roughness due to each pair. The joint effect of all these roughnesses constitute the dissonance of the combinations. If there be no dissonance the combination is described as a perfect concord. When dissonance is present, its amount will decide whether the combination has to be classified as an imperfect concord or a discord.

Further the number and arrangement of the partial tones in the composite tone also decides the consonance or dissonance. Chords which sound well on flutes or strings will be impossible in clarinets. Again, when two composite tones co-exist we saw that combination tones will be produced. Dissonance may arise due to the combination tones also. Helmholtz has investigated such cases also.

The explanation given by Helmholtz as to why consonance is always associated with ratios of small numbers can be seen now. That two composite tones or notes which are an octave apart form a perfect chord is a well established musical fact. Helmholtz points out that only by exactly satisfying the assigned simplest numerical relation of 2 can the partial tones of the higher note be brought into exact coincidence with the partial tones of the lower. When this is the case all beats and consequent dissonance are prevented. The next nearest approach to such a concord is the fifth. Then comes the fourth and so on. We shall consider now the case when three notes are produced at a time. In this case the probability of rough beats is greater than with two notes and hence the number of consonant triads will certainly be smaller than the number of consonant chords of two notes. A triad consists of three intervals, one between the lowest note and the middle note, another between the middle note and the highest note, and a third between the lowest and the highest. If any one of the three intervals is dissonant the triad becomes

dissonant. The number of consonant triads possible within an octave can be easily calculated and it is found that six consonant triads are available. Expressing them by means of numbers they sre 3:4:5, 4:5:6, 5:6:8, 10:12:15, 12:15:20 and 15:20:24 respectively. But these six triads are not all independent. If we replace the lowest note of 3:4:5 by its octave we have 4:5:6 and if we replace the lowest note of 4:5:6 by its octave we have 5:6:8. Thus the three triads 3:4:5, 4:5:6 and 5:6:8 may be regarded as simply different positions of a single triad which we may represent by 4:5:6. This is known as a Major Triad. In the same way we can see that the three other triads may be regarded as different positions of the triad 10:12:15 which is known as a Minor Triad. Thus we see that if we restrict ourselves to triads in which no notes are as far apart as an octave there are only two kinds of consonant triad, Major Triads and Minor Triads. The imperfect nature of Minor Triads compared to the Major Triads according to Helmholtz's investigations is due to the different ways in which combination tones enter in the two cases. Sometimes four part chords are also used in harmonic music. It can be easily seen that all consonant tetrads must be either Major or Minor triads to which the octave of one of the tones has been added.

Introduction of Tempered scales for the sake of unlimited facility of modulation in keyed instruments has considerably changed the border line between consonance and dissonance in western

music. Many chords which were thought discordant at first have become common usage. It is said that good orchestras in western countries even now do not play in Tempered scales. Helmholtz goes to the extent of saying that the music based on any Tempered scale is an imperfect music. Instruments like the Piano and organ have become so popular that it is too late for them to go back to pure intervals and perfect chords. A poet has said that it is only "a low sun that exhibits glorious colours" and it is no wonder that imperfect harmony has captivated Western ears.

CHAPTER XII

TIMBRE

With very little practice one is able to recognise the different musical instruments even when they are producing tones of the same loudness and pitch. This distinguishing characteristic of a tone is known as its timbre or quality. There is an almost infinite variety of tone quality; not only do different musical instruments have characteristic qualities but individual instruments of the same family *viz.*, violin family show considerable variations in quality. Even in a single instrument tones of the same pitch can be produced with different qualities. Among all the instruments the human voice stands supreme in its remarkable ability to produce varied tone qualities. The physical basis of this characteristic of a tone remained a mystery till Helmholtz investigated it.

It has long been recognised that almost all the sounds we hear are composite sounds. It was Ohm who first showed that the human ear can perceive only pendular vibrations as simple tones. Because of this property it is claimed that it is able to recognise the different partial tones contained in the composite tone. The partial having the lowest frequency in the composite tone is called the fundamental and the others harmonics when the latter have frequencies which are exact multiples of that of the fundamental. Helmholtz proved by his investigations that the timbre of a sound is determined by the proportions in which the various harmonics are heard in it.

Helmholtz made use of the principle of resonance for his investigations. This principle can be easily understood from the following illustration If we blow across the open end of a tube we can hear a distinct tone. Its pitch will be determined by the length of the air column in it. The air column can be induced to vibrate if any musical tone of this same frequency or pitch is produced near its mouth. This is then called a resonator for that sound. The resonators which Helmholtz used were hollow spheres made of either glass or metal. These resonators are now in general use and are called Helmholtz resonators. It has two openings; one is the mouth and the other has a small tube protruding from it. This is for inserting it into the ear. For his investigations Helmholtz took a number of these resonators of different sizes depending upon the pitch of the sound he examined He was able to find out the partials heard in that sound by observing the resonance in the different resonators by inserting every one of them in his ear.

Later workers discarded the spherical resonators in favour of cylindrical resonators because the volume of this type was easily adjustable. Helmholtz's method of investigation is useful only for identifying and establishing the existence of partial tones which would otherwise be faint or inaudible. But their relative strengths could not be found out. In order to make quantitative observations later workers replaced the ear by other devices. The resonator consists of two tunable cylindrical vessels connected by a short neck. To detect the resonance when this is exposed to the influence of a note having a pitch to which

it is tuned a thin circular disc is suspended in the neck by means of a fine quartz fibre. The resonator

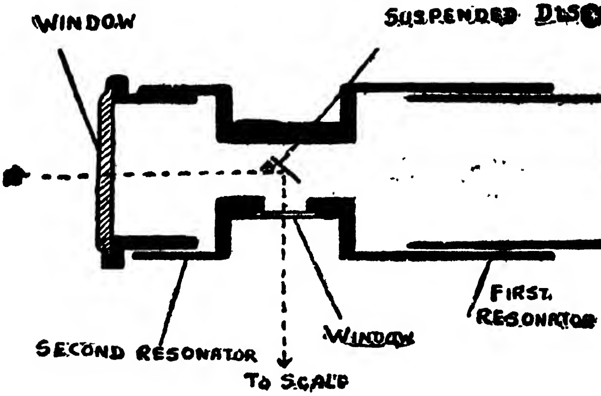


Fig. 18
Rayleigh Disc and Resonator.

is provided with glass windows in the neck and in the ends. A beam of light can be arranged to undergo reflection in the disc. A scale is provided to catch the reflected image on it. When the air inside is set in vibration the amount of resonance is noticed by the deflection of the image on the scale.

Another device is also used in this type of resonator. An exceedingly fine platinum wire is placed in the neck in the form of a grid. An

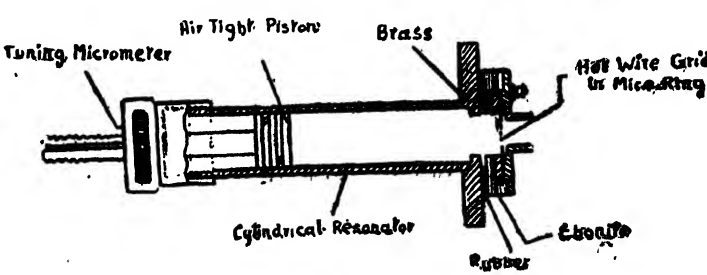
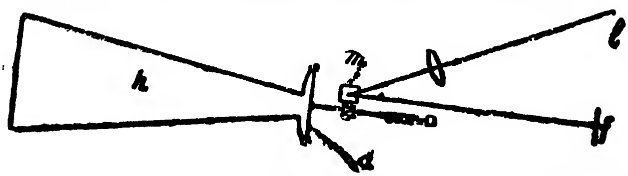


Fig. 19
Tucker hot wire Microphone.

electric current is sent through it to heat it just below red heat. When resonance happens the pronounced oscillatory movements in the air in the neck cools the wire and this decreases its electrical resistance. The resistance can be measured separately and the amount of resonance determined.

The disadvantage in the above instruments is that a large number of resonators is necessary to cover the entire frequency range in music. To avoid this another method has been devised by Miller and others. This has a different principle. It is a common knowledge that speech and music are conveyed to the ear through the surrounding air. Just as ripples spread outwards from a stone thrown into a tank, waves spread in the air from a sounding source. These sound waves possess certain characteristics. These are length, height and shape. The length of the waves is determined by the rate of vibration while the loudness depends on the amplitude or height of these waves. The shape or form of these waves is determined by the mode of vibration. A tuning fork when properly mounted on a resonance box sends out waves of the simplest shape. The sensation produced in our ears due to the impact of these waves is also simple or pure. This is the simple tone referred to by Ohm. Almost all the other sounds are transmitted through the air by very complicated wave forms. It has been shown by Fourier and others how an analysis of the wave form of a particular sound reveals which harmonics are present and what their strengths are. Wave form is therefore an indication of timbre. So obtaining the wave forms becomes necessary for deciding the quality of all sounds.

Various instruments have been devised to obtain records of the sounds from different sources. In all these a diaphragm is fixed at the end of a horn which acts as the senstive receiver. A diaphragm is a thin sheet of elastic material. It must respond with equal facility to tones of a wide



h—horn
d—diaphragm
m—mirror

Fig. 20
Phonodeik.

l—light ray
f—camera

range of pitch and to a great variety of tone combinations without introducing fictitious frequencies. But actually this is not the case. The diaphragm and the horn have their own natural periods of vibration and response to impressed waves of frequencies near these regions will not be faithful. However these instruments have yielded interesting results concerning the analysis of tones. The best among these instruments is the one devised by Dayton Miller. In this a glass diaphragm is at the end of the resonator horn. To its centre is attached a very fine wire, which passes over a pulley at the end of a minute steel spindle and is held tight by a spring. To the spindle a small mirror is fixed to which light from a pinhole is directed. The reflected light is made to fall on a moving film in a special camera. When the diaphragm moves under the action of a sound wave, the mirror is rotated by an amount proportional to the motion and the reflected spot of light traces the record of the sound wave on the film. The camera

is specially designed and has several shutters. The revolving drum carrying the film is rotated with a steady speed by an electric motor and there is a commutator on the revolving drum which opens and closes the shutter. Miller obtained curves covering the entire scale for the flute, violin, horn and human voice.

Nowadays the cathode ray oscillograph is extensively used for recording purposes. This consists of a vacuum tube one end of which is cylindrical while the other is broadened out. At the latter end is a fluorescent screen. There is a filament fixed at the narrow end which on heating by an electric current sends out a beam of electrons. Electrons are very minute particles carrying negative electricity. This electron beam is directed axially on the fluorescent screen. Where it falls it produces a bright spot. Two pairs of plates are contained in the tube which when connected to an alternating or varying electric field will make the bright spot oscillate

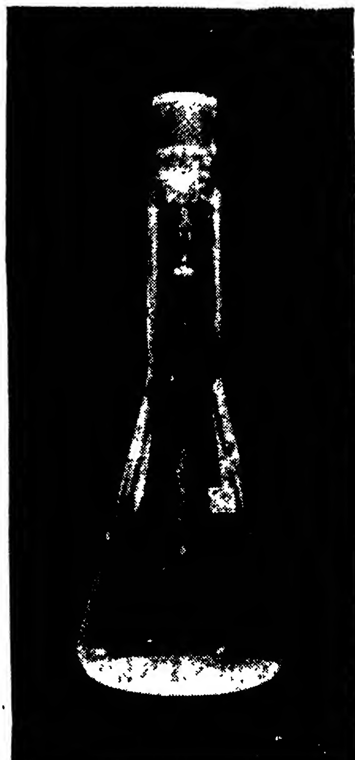


Fig. 21
Cathode Ray Oscillograph.

either horizontally or vertically. Before recording, the sounds are first picked up by a microphone which converts the sound vibrations to varying electric field. This alternating field is applied to one pair of plates in the oscillograph. The oscillations of the bright spot are then recorded in a film moving in front of the fluorescent screen. In this mode of recording the defects introduced by the horn and the diaphragm in the previous methods are eliminated since recording is directly done by the electron beam.

Curves and wave forms obtained by the above methods for the various sounds are analysed for finding out the number of partials and their strengths. The technique for analysing the wave form into its constituent simple tone curves is based on a theorem known as Fourier's theorem. This may be stated in a number of ways. It shows that every curve can be exactly reproduced by superposing a number of simple tone curves. Based on this a large number of graphical methods have been devised to find out the number of constituent simple tones in the original sound and their relative strengths. These methods are very tedious and hence a large number of mechanical devices have been invented which perform this task of harmonic analysis. Among these the instrument devised by Henrici is the best. For doing the analysis the curve is placed on the base of the instrument and its pointer is made to trace out the waveform. The relative amplitudes of the required number of harmonics are read off directly from the instrument.

With this instrument Miller investigated the waveforms of a number of musical instruments. Electrical harmonic analysers have been recently designed which analyse complex sound with far more sensitiveness and accuracy. This method was used in the Bell Telephone laboratories for analysing musical tones and speech sounds. The action of an electric harmonic analyser can be best understood by taking the ordinary radio set as analogy. After switching on the set if we turn the tuning knob through the whole range of frequencies of wavelengths we will hear one station after another. Sounds are heard only when the set is in perfect resonance with the waves falling on the aerial. They are not heard in other positions because the waves falling on the aerial then are not in resonance with the set. Their turn comes in when the tuning dial points elsewhere. Thus we analyse the waves falling on the aerial by sorting them out according to their wavelengths or frequencies. In the same way the electrical analyser functions by making use of the principle of electrical resonance. Before using it the sound waves are converted into electric waves by means of a microphone. These are then transmitted into a suitable network of tuned electric circuits. Maximum responses will recur at frequencies which coincide with the frequencies of the components in the complex wave. An automatic photographic recorder registers the amount of current passing through the different circuits at the respective frequencies. From this record the relative amplitudes of the components of the complex sound wave are readily determined.

Helmholtz, Miller and Harvey Fletcher have obtained valuable results concerning the tonal qualities of various sounds. Helmholtz conducted the analysis with his resonators, Miller with his phonodeik and Fletcher with his electrical harmonic analyser. Though their methods are different they have obtained more or less the same results which make it possible to describe the distinguishing characteristics of tones of several instruments. They have found that the quality of these tones depend largely on the way in which they are generated and controlled by the player. The sound producing parts of a musical instrument perform two distinct functions. Certain parts generate the vibrations while the others amplify them The latter are designated as resonators. These take up the energy of the vibrations of the generator and magnify them by operating on the larger quanity of air. In almost all the instruments the resonators are so designed that they respond to tones of any frequency and to combinations of these. The material of these resonating parts has been found to influence the quality considerably. They have also found that the mode of generating the sound influences the quality. Musical tones may be generated on strings by striking or plucking or bowing. The nature of the stroke, the place struck, the density and elasticity of the string and numerous other factors control the quality. Tones are generated in the case of the flute and other wind instruments by blowing against a sharp edge. In some instruments reeds are used to generate the vibrations. Human lips are used to produce the

sound in the case of brass instruments. All these different modes of initiating the sound make gradations of quality possible.

For everyone of these instruments Helmholtz, Miller and others found out the number of harmonics entering into its tone composition and also their intensities. They found six partial tones in the case of pianoforte tones the first three being stronger than the others. Charts known as acoustic spectra were drawn for a number of tones to give complete information regarding not only the total intensity of a complex sound, but also the frequencies and intensities of the different components. In the case of the violin they found about ten partials entering into its composition. They also found its prime tone invariably more powerful than that of the piano or harp. It is claimed by them that the great

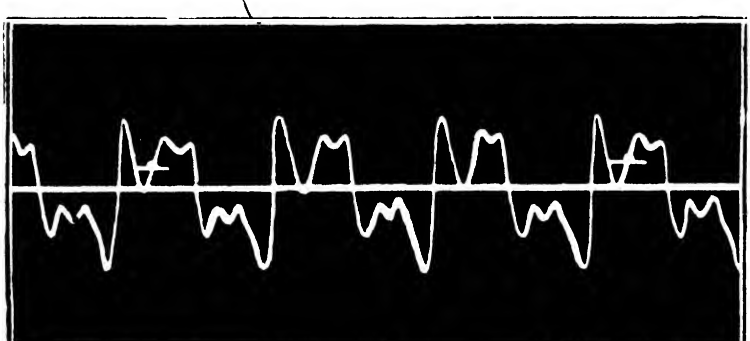


Fig. 22
Photograph of the Tone of Clarinet. (Miller)

advantage which the violin has over other orchestral instruments in expressiveness is due to the great control which the performer has over the production of these partials. The results show that

the flute gives out the simplest sound with a single partial and it is to this fact they ascribe its soft quality. They say that it is this paucity of partials that causes its sound to blend more rapidly with

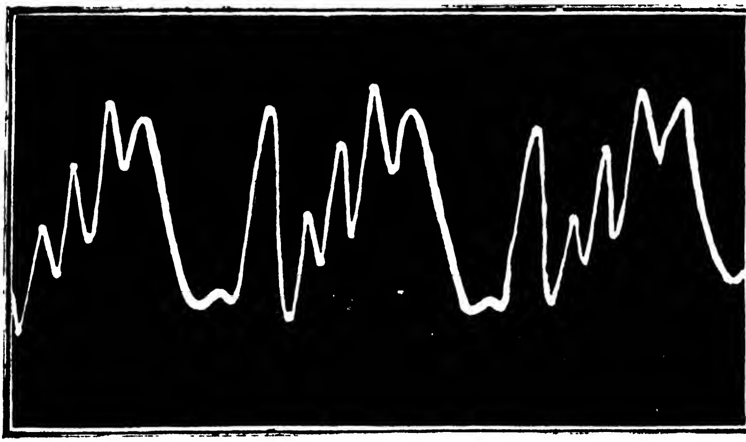


Fig. 23
Photograph of the Tone of Oboe. (Miller)

that of other instruments. Their study reveals the largest number of partials (more than twelve) in the case of clarinet. They also find that the higher partials have greater strength. In the case of the human voice, the vowel sounds have been more extensively investigated. The vocal mechanism which serves as the sound source consists not of one but a group of mechanisms. The most important among them are the vocal cords. They are the muscular ledges in the throat which are situated at the top of the wind pipe leading to the lungs. They are set in vibration by the air passing between them from the lungs. The other mechanisms are the tongue, teeth, lips and the resonance chambers

in the head. Every one of these imparts its characteristics to the sounds generated by the vocal cords. These sounds can be divided into vowel sounds and consonants. It has been noticed that in the formation of vowel sounds the adjustment of the resonance space of the mouth and pharynx is particularly important while in the case of consonants the position of the tongue, lips, and the soft palate alone are important. The above mentioned scientists have done both analysis and synthesis of vowel sounds. Their conclusion regarding their timbre is briefly this. Every vowel is characterised by certain overtones. The absolute pitch of these characteristic overtones is constant since it corresponds to certain natural vibrations of the mouth cavity in the position necessary for the production of the vowel sound. Vowel sounds differ therefore from the sounds of most other musical instruments in that the strength of the overtones does not depend upon their position in the harmonic series, but rather upon their absolute pitch. They found for some vowels a single prominent overtone and with others two prominent overtones. They checked their conclusions by reproducing the vowels synthetically. Fletcher investigated the consonant sounds more elaborately. He found three characteristic frequency regions. They have thus established the physical side of both the musical tones and speech sounds.)

(Though it has been established beyond doubt that the quality of all musical tones and speech sounds depends on the proportions in which the

different harmonics enter into their composition, it must be admitted that the fringes alone of this problem have been touched. Only when we are able to produce and blend consciously the different harmonics to obtain any desired quality can we say that we have understood the problem. As has been pointed out earlier, the factors controlling the production of these harmonics are enormous. Taking for example the violin we know how complicated are the relationships between the different sound producing parts. Many details of the action of the violin still remain to be cleared up. Unless the effect of all these controlling factors are understood we cannot control the quality of its tone. The same thing applies to other instruments and voice. Thus it must be concluded that quality is only a partially understood mystery.

CHAPTER XIII

HALLS AND AUDITORIUMS

In recent years the study of the acoustic properties of large halls and auditoriums has come into great prominence. It has helped architects to draw designs with perfect acoustic conditions. In olden days when performances and meetings were held in open air theatres there was no need to take any precautions. The sound waves from the stage reached the listeners by direct radiation and they never returned. But the modern auditorium is an enclosed space. The sound waves in this case after reaching the listeners strike the boundaries of the auditorium and undergo reflection. The objects in the auditorium also reflect them. As sound travels quickly at the rate of 1100 feet per second, the waves are reflected not once but many times before they disappear. These numerous reflections set up distortions and unequal intensities in the sound heard in the different parts of the auditorium. Moreover, the boundaries may vibrate in sympathy in which case the effects of their vibration also add to the distortions and unequal intensities in the sound heard. If there are big pillars or obstacles in the auditorium they also modify the quality of the sound heard by the listeners sitting behind them. All these defects have to be corrected to ensure good hearing in the auditorium.

Everyone who has noticed the movement of water waves with crests and troughs can easily recognise the speed with which they travel. Sound waves also travel in air in the same way but unlike the water waves they consist of alternations of condensation and rarefaction. These are formed regularly and they travel outwards at a speed of about 1100 feet per second. When these waves are formed in an auditorium they undergo at least two or three hundred reflections before they disappear. Echoes may be heard as a result of these reflections. It has been found that echoes are not noticeable when the time of interval between the arrival of the direct sound waves and the reflected sound waves is less than about one-fifteenth of a second. Since the speed of the sound waves in air is about 1100 feet per second this amounts to a path difference of 75 feet between the direct and reflected sound waves. Thus the question of echoes will not arise except with large halls and auditoriums. If curved surfaces are present in the auditoriums the echoes from such a surface will be enhanced at the place near the focus. Even when there are no echoes from the curved surfaces, the surfaces will focus the sound waves to some regions to the detriment of others. A hall with an approximately rectangular section alone will be free from these focussing effects. By drawing a design of the auditorium such that all possible paths, direct, once or twice reflected, by which the sound can reach a listener are nearly equal, echoes can be avoided completely.

Sometimes "dead spots" may be noticed in an auditorium. At these places the direct sound waves and reflected sound waves interfere and destroy one another with the result that no sound is heard by the listener sitting there.

For spotting undesirable foci, echoes and dead spots in an auditorium or hall three experimental methods are employed *viz.* (1) the geometrical method (2) the ripple tank method and (3) the sound pulse method. Both vertical and horizontal

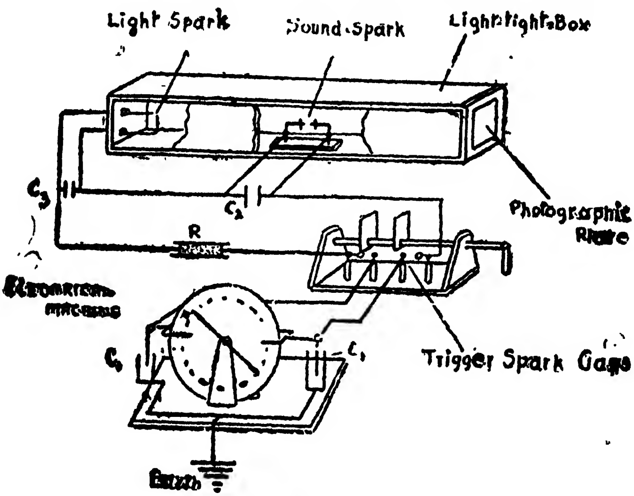


Fig. 24
Sound Pulse Photography Apparatus.

model sections of the building are constructed for the purpose. The course of the sound waves inside the model is studied. In the first method the general directions of likely echoes are deduced from simple geometry based upon the usual optical laws of reflection. This method is not likely to give full details. For instance, details regarding

the spreading of sound waves outside the limits imposed by the geometrical optics cannot be obtained by this method. In the second method the behaviour of sound waves is understood by water wave analogy. The model sections of the auditorium are laid on the glass bottom of a tank containing a layer of half an inch of water. Ripples are sent out from a point corresponding to the position of a speaker in the auditorium. This is done by operating a plunger by means of an electro-magnetic device. When the plunger is withdrawn from the water, it starts a short train of waves which proceed outwards in circles and are reflected at the wooden boundaries of the model. Light from a powerful source is made to pass upwards through the glass bottom of the ripple tank and this casts a shadow of the waves upon a screen placed above the tank. The progress of the waves is thus studied visually. The whole course of these ripples can be followed by taking a cinematograph film of the motion. As the behaviour of sound waves is similar to that of the ripples details regarding reflections at the boundaries of the model sections are thus obtained. The sound pulse method is easily the best among these. Here the actual progress of the sound waves within the model sections are photographed. In a light tight wooden box containing the model section of the auditorium two electrodes are placed and the sound heard when an electric spark passes between them is used as the source. This gap is located in the middle of the box. At one end is another spark gap across

which a light flash can be produced at will at a fraction of a second after the sound spark has "gone off". At the other end of the box is a photographic plate on which a shadow of the sound pulse is cast. By taking a series of photographs at various time intervals of lag between the sound and light sparks the course of the sound waves in the model can be followed easily. A cinematograph film of the motion of these waves can also be taken.

After spotting undesirable foci, echoes and dead spots they are removed by suitable means. Two methods known as "medicinal method" and "surgical method", are adopted for correcting these defects. The surfaces which give rise to echoes, foci and dead spots are covered by absorbents to enfeeble the reflected waves. If this is not satisfactory the surfaces are broken at those places, so that the continuity is destroyed. Sound waves falling at those places will then be scattered instead of being regularly reflected.

There is a more serious defect arising from reflection. This is the excessive persistence of sound due to insufficient absorption by the boundaries and objects in the auditorium. It is called reverberation. Everyone can notice this defect in our temples and empty houses. The stone walls of the temple reflect back the incident sound waves without absorption so that the residue of the sound continues for several seconds. In empty houses it will be noticed that this reverberation vanishes as soon as the floors are covered with carpets and

the rooms are filled with furniture. The time required for the sound to become inaudible after the source is discontinued is known as the time of reverberation. Every hall or auditorium has a time of reverberation. The hall is said to have excessive reverberation when this time is too long. This is not a total defect. It is a serious defect where speech is concerned but it is actually welcomed for purposes of music. Two music halls may be exactly similar in size and shape. In one the performers will play with zest and in the other they will feel a want of sympathy, the reason being the difference in the times of reverberation for the two halls. This defect was not well understood till Professor Sabine of America found out experimentally how this time of reverberation varies with the volume of the hall, the power of absorption of the walls and the objects in the hall. By his laborious study of the various halls and auditoriums in America, he found out a formula for the time of reverberation. This was found to depend only on the volume of the hall and area of the walls and their power of absorption. It was not found to depend on the positions of the source or the observer in the hall. It was also found that the effect of a given absorbent was independent of its position in the room. Taking an open window of 1 square foot in area as his unit of absorption he determined the absorption co-efficients of various materials by ascertaining the area of open window which gives the same reduction of reverberation as the known area of the test material. It is intriguing

to learn that he found each member of an audience is equivalent in absorbing power to about four and half feet of open window. Thus it will be seen that the audience will contribute the greater part of the absorbing power of an auditorium!

There are a number of methods for determining the absorbing power of different materials. In one method the material in question is placed at one

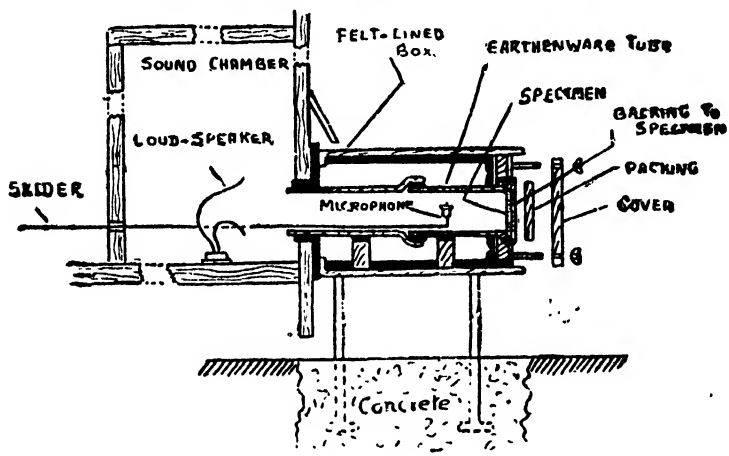


Fig. 25

Stationary Wave apparatus for measuring reflecting Powers.

end of a long pipe while a loudspeaker delivers sound into the other at constant pitch. Sound waves proceeding from the loudspeaker travel upto the other end and are reflected by the material in that end. The reflected sound waves and incident sound waves overlap and produce what are known as stationary waves with nodes and antinodes each set half a wave length apart. There will be maximum pressure variations at the nodes and no pressure variation at the antinodes if the material

is a perfect reflector. With an imperfect reflector like a porous tile the nodes show a reduced pressure change while the antinodes now exhibit some pressure charge. There are a number of instruments to measure these changes. From a knowledge of the values for the changes in pressure we can calculate what fraction of the sound of that frequency is being absorbed by the specimen. In another method known as the Watson method, the amounts of sound reflected and transmitted by the specimen are both measured. Here the material is let into a massive wall and a beam of sound is directed to the specimen. On the same side of the material as the source a large parabolic cone is arranged to collect the sound from the reflected beam and concentrate it on to a microphone at the focus of the paraboloid. This registers the amplitude in the reflected beam. A similar collector and detector on the other side of the material records the transmitted amplitude. After removing the material the sound beam is allowed to fall directly on the detector which is on the far side of the material and the intensity of the original beam is estimated. With these measurements both the absorption and transmission co-efficients are calculated.

With the knowledge of the absorption co-efficients of almost all the building materials it is possible to control the reverberation in halls and auditoriums. The time of reverberation for a hall can be calculated from Sabine's formula. To every hall there is an acceptable time of reverberation,

The time acceptable for speech is different from that of music. A committee of musical experts has to fix this optimum time of reverberation for that hall. The difference between the calculated time and optimum time is made up by arranging the correct amount of absorption by the materials and persons within it. There are a number of materials available in the market for this purpose. Fibrous boards, asbestos, slag-wool are some of the common absorbents used. Special acoustic plasters are also available. These are made by incorporating chemical agents in the mixture which will produce bubbles of gas during the manufacture and so create number of holes in them after manufacture. Some of these plasters are claimed to absorb nearly seventy percent of the incident sound. As has been pointed out earlier the audience contribute the greater part of the absorption. Extreme variation in the numbers of the audience may be atoned for to some extent by the provision of curtains. These can be drawn aside when the numbers are sufficient. Sometimes upholstered seats are also used to make up the absorption yielded by the absent sitter. If on the other hand the auditorium is found to be deficient in reverberation its ceiling and walls ought to be made more massive and smooth to have good sound reflecting property. Nowadays this deficiency is made up by increasing the sound output of the source to the desired level with the help of microphone and loudspeakers. When an amplifying equipment is used it must amplify only to an extent such that

the remote listeners can hear with comfort. If there is excessive amplification it will give prominence to the low pitched tones and thus the quality of the sound heard will be affected.

Besides the defects mentioned above there are a few others of minor importance. It is well known that all sounds are composite. The partial having the lowest frequency in the composite sound is called the fundamental and the others are called overtones. Helmholtz has proved by his investigations that the quality of a sound is determined by the proportions in which these overtones are heard in it. A composite sound on meeting a reflecting wall will have its components absorbed unequally so that the reflected sound does not have the same tone structure as the original sound. Hence due to reflection the quality of the sound is altered to some extent. If there are big pillars and sharp corners the quality of the sound is again affected. The higher overtones are cut off from the composite sound when it passes behind a pillar or round a corner. To avoid this the auditorium must be built without massive obstacles and corners inside it. If there are resonant surfaces they should be suitably damped; otherwise sounds of appropriate pitches will be reinforced with unpleasant results. Usually such resonant vibration is noticeable only when the source is very powerful such as the organs in churches. Sometimes resonance is resorted to in some halls deliberately. It is said in the Leipzig Gewandhaus the orchestra

is placed on a raised platform which is deliberately connected by strong wooden beams to the panelling of the hall. In this way, the walls of the building are made to act as resonators. Resonance may also happen in the air inside the hall or auditorium. It used to be said that a speaker can be heard with ease as soon as he adjusts his voice to the pitch of the room. But this happens only in small rooms and not in halls and auditoriums.

CHAPTER XIV

GRAMOPHONE RECORDING

Gramophone recording is the oldest of the three methods available now for making permanent records of music. The optical and magnetic methods are recent inventions. Even gramophone recording has attained its present perfection only after hundreds of experiments. The discovery of the radio valve alone has contributed considerably towards this perfection. It was Leon Scott who first showed in 1857 that sound could be recorded. He named the invention as the Phonautograph. It consisted of a barrel shaped cylinder to focus the sound on a light membrane fixed at its end. The membrane actuated a needle which drew the vibration curve on a piece of blackened paper wrapped on a rotating drum. The drum was rotated in such a way that it slowly advanced making it possible to take traces on it. Edison improved this invention by recording the sound in such a manner that it could be reproduced. Instead of a blackened paper he used a sheet of tin foil to cover the rotating drum on which he obtained the vibration curve. To reproduce the sound another similarly mounted needle was made to move over this vibration curve. As the needle traced the curve its vibration was communicated to the membrane and the sound was reproduced. Edison named this instrument as the

'phonograph.' He made many improvements in this model. One important improvement was the use of wax cylinders to take the traces. In 1887, Berliner changed the cylinder to a flat disc and recorded the sound on it. After this change only the instrument came to be known as the gramophone. A great improvement was made in these machines in 1925 when mechanical recording was replaced by electric recording. The older method of mechanical recording had its limitations. The device employed in this method consisted of a membrane and a system of levers which swallowed much of the sound energy. So it became necessary for the performers to get very close to the mouth of the horn. This is an impossibility when a number of instruments had to be recorded. There is still another drawback in this method. All bodies have their own natural periods of vibration and when a note impinges on them of the same frequency, they will resonate. Due to these resonances occurring in the horn and diaphragm the sound recorded became distorted. This was overcome to a great extent in the electrical recording. By the discovery of the radio valves it was made possible to amplify the sound energy to any extent and this avoided the crowding of the performers near the horn. Even the faintest sounds and the finest shades can be faithfully recorded by the electrical method. We shall now see the details of this new method of recording.

The first important requisite for this method of recording is the studio. All gramophone

companies bestow great attention on the construction of their studios. They will all be built so that extraneous sounds are prevented from entering them. Double walls will be specially constructed to insulate the room and double doors and triple windows will be provided. Suitable acoustic materials will be employed for panelling purposes. After constructing the studio a number of factors concerning the sound distribution will be evaluated and necessary precautions taken to control them. The manner in which the distribution of sound is affected by reflection from the walls, the existence of echoes, the amount of reverberation present, the frequency characteristic of the material lining the walls will be some of the factors evaluated. Of all these the most important factor is the time of reverberation for the room. Excessive reverberation and insufficient reverberation are both unacceptable. The correct amount of reverberation needed for good acoustics varies with the nature of performance. It has been found that the degree of reverberation required when recording speech is about ¾ second whereas it is about a second when recording vocal music. Even these times hold good only for the frequency 512. The necessary amount of reverberation will be judged carefully and will be secured by suitable rotating shutters, curtains and so on. During recording no wooden chairs or music stands will be used in the studio as they are likely to creak. Special all-metal furniture will be used.

The next step in electrical recording is the selection of a microphone and the amplifying equipment. The microphone is the electrical

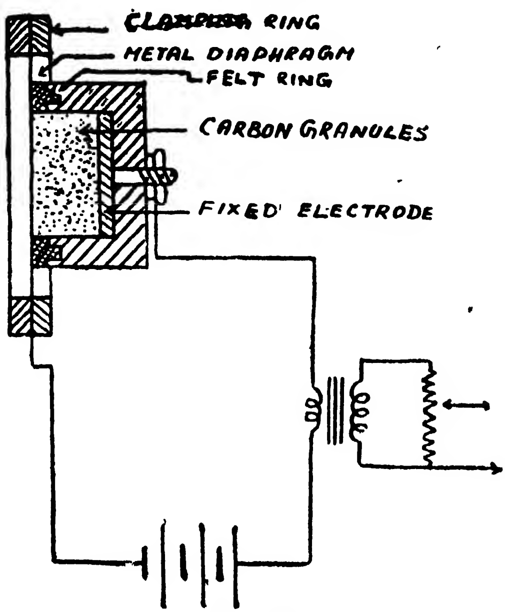


Fig. 26
Carbon Microphone.

counterpart of our ear. It is so constructed that the diaphragm inside it vibrates when sound waves fall on it. The vibration of this diaphragm is used to control an electric current so as to produce electric vibrations corresponding to the original sound waves. This fluctuating electric current is magnified many times by suitable radio valves. Three kinds of microphone are in use namely, the carbon microphone, the condenser microphone and the moving coil microphone each with peculiarities rendering it suitable for particular work. The

amplifying system consists of an arrangement of radio valves and associated components for coupling these valves to each other and to the microphone. The amplified fluctuating current is then conveyed by wires to the recording room which is adjacent to the studio.

The recording instrument is both delicate and complex. Every little detail in the construction of this instrument is carefully studied by all gramophone companies because the success of good recording depends largely on this instrument. The turn table and the electro magnetic cutter are its two main features. It is the turntable that bears the flat wax disc. Unless this table rotates at a very steady rate without any fluctuations in its speed the recording will be spoiled. Hence great care is taken in selecting a suitable motor for the driving mechanism. The recording speed adopted by all companies for ten inch and twelve inch records is 78 revolutions per minute. This speed has become a world standard. Recently a recording speed of 33-1/3 revolutions per minute has been adopted in America by some companies. There is considerable hesitation on the part of the British companies to accept this new speed. Though a record taken at 33-1/3 revolutions per minute lasts longer the quality of recording deteriorates due to the reduction in speed. However, it is considered likely that the American practice may become popular for at least home recording purposes. The cutter used

consists of a coil system known as armature pivoted in the gap of an electro magnet. The amplified fluctuating current from the microphone flows through the armature coils and makes the armature vibrate in exactly the same way as that of the diaphragm of the microphone. The sharp sapphire cutter is attached to the lower end of the armature and it traces its vibration on the rotating wax disc placed underneath it. As the cutter vibrates it is also drawn across a radius of the wax disc at a uniform rate of translation by means of a train of reducing gears.

The wax used for recording is again another important factor which requires great skill in its preparation. There are a number of firms which specialise in its production and they sell good wax blanks to the smaller gramophone companies. The exact constitution of the recording wax is kept as a secret. A number of constituents such as bees-wax, shellac, vaseline, hard paraffin etc., are used in preparing it. Different formulae are given for combining these constituents to secure good wax blanks. For obtaining them the constituents are melted and mixed first and the molten wax is poured into circular metal trays. Special precautions are taken during its cooling especially to prevent dust coming into contact with it. After hardening the blanks are trimmed and polished by a special machine. They are then transported in felt-lined, vibration-proof boxes for recording. Before recording commences they are placed in shelves in a wax oven which is electrically heated. They are all kept there at a constant temperature.

When a session is about to commence the recording engineer places a polished wax blank on the turn table and starts the motor. He will then take a trial cut on the edge of the wax. After examining it under a suitable instrument he will adjust the depth of the cut and the cutting pressure. According to the length of the programme to be recorded he will adjust the pitch of the spiral and the gear mechanism. He will also see whether the suction plant for removing the shavings is working properly. During this period a green light will be switched on both in the studio and outside to indicate that the recording is about to begin. After adjusting everything in the recording room the engineer will switch off the green-light and switch on the red-light. The programme will then start and as the recording goes on the engineer will be listening from his sound-proof room by means of head phones. He will also see what is happening in the studio through a spy hole provided with a double window. This will enable him to help the performers maintain the correct orientation towards the microphone. He will also check the turn-table speed constantly. For this purpose white lines called stroboscopic lines are engraved on the periphery of the turn table. At the right speed these lines will appear stationary.

The next step in the recording is to transfer the subtle trace of the sound waves from the wax disc to a metal stamper. This is done again with the help of electricity. The wax disc, now known

as the wax master, is made conductive by coating its surface with fine graphite powder. For doing this the disc will be placed on a turn-table which is rotated slowly. The graphite will then be applied by hand with the help of a soft camel hair brush. It requires great skill to do this. Insufficient rubbing would fail to produce the necessary even coat of graphite and too much rubbing on the other hand would damage the surface. Nowadays a specially ground bronze powder is used in the place of graphite. After removing the excess of graphite or bronze by another brush, it will be placed in an electrolytic bath. The acid copper bath which is more commonly used will contain copper sulphate and sulphuric acid. It is well-known that when a current of electricity is passed through such a solution copper will be deposited on the plate from which the current comes out of the bath. This plate is called the cathode. In big factories tanks of suitable sizes will be arranged in rows in the galvano rooms and electrolytic bath solution will be taken in them. The suspended impurities in the bath which give rise to rough coatings on the cathodes will be eliminated by constant agitation. The temperature of the bath also will be controlled. When the necessary amount of copper deposition has taken place the current will be stopped and the wax master will be removed from the bath. The metal coat is skilfully pealed off by hand. The pealed off shell is called the copper-master. This is a negative. It is not directly used for making records. A positive is prepared from this negative

by further electrolytic deposition. This is stripped from the copper-master in exactly the same way as the copper-master is stripped from the wax master. This is called the 'mother'. A number of such mothers are produced and from these mothers stampers are produced by further electrolytic deposition. Nickel and chromium salts are used for bath solutions in the preparation of these stampers. Though the technique of chromium plating is not yet fully developed chromium stampers are preferred because they last about twice as long as nickel plated stampers. The stampers are negatives and the records produced from them will be therefore positive and will play on a gramophone

Before observing the details of record pressing it is necessary to know a little about the raw materials used for the record. The most important raw material used as the chief binding agent is shellac. All the valuable properties needed for taking a good impression from the stampers are possessed only by shellac. The softness and evenness of flow while under pressure, the easy working properties on the hot plate, the high gloss and final hardness of the finished record, are all due to the presence of shellac in the record material. Shellac is obtained from lac. Lac is a sticky substance. India is the sole lac producing country. This substance called by the chemists as resin is exuded by lac insects which thrive on certain types of trees found in Bihar and Central Provinces. The minute larvae fasten themselves on the young

shoots and barks of these trees and draw their nourishment from the sap. From the moment they commence sucking they exude this resinous secretion like silk worms. A continuous covering of this resin is formed on the twigs, barks etc. In the meantime the male insects fertilize the female ones and die. It is only after fertilization the bulk of the lac is exuded by the female insects. The eggs spread to other trees and infest them also. Another life cycle commences. Sometimes the lac-crusted shoots are cut off the trees and temporarily tied on the branches of other fresh ones to help the young ones to find their settling places. The old lac crusted twigs, sticks and barks are collected and ground into a fine powder. It is then sifted and washed in water to remove the dead insects and other impurities. The lac is then collected in cloth bags and melted near a flame. The melted resin coming out of the pores of the cloth is stretched into thin flakes which are then allowed to dry. These flakes are known as shellac.

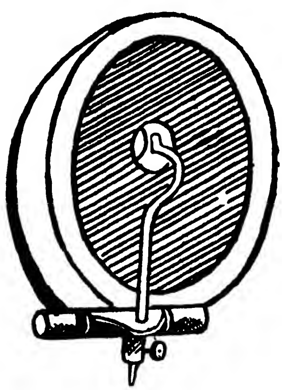
Along with shellac small quantities of other resins are also used as secondary binding agents in preparing the record material. Congo copal is one of the resins used as it is found to blend very well with shellac. A natural resin obtained from pine trees was at one time used by almost all gramophone companies for increasing the fluidity of the record material. Recently synthetic resins are being tried as shellac substitutes. To increase the body of the record material certain substances

are used as fillers. Slate dust, carbon black, bone black, calcium carbonate are some of the substances used as fillers. These are called powdered fillers. Other substances known as fibrous fillers are also incorporated into the record material to decrease the brittleness and shrinkage. The resins, the powdered fillers, the fibrous fillers are all finely ground in mills, sieved, and mixed by means of machines. Only large gramophone companies take the trouble of preparing the record material themselves. There are a number of firms which supply these raw materials in a finely ground condition and the mixing alone is done by many companies.

The stampers are then fixed in the jaws of a steam heated press. When the desired temperature is attained, a lump of recording material is placed on the mould and the press doors are closed by hydraulic power. A pressure of about a ton per square inch will be applied. Side by side with this application of pressure it will be allowed to cool till it hardens. The pressure is then released and the two jaws forced apart and the gramophone record will be removed. As the record pressing is going on some of the records will be tested by playing so that if defects have occured they may be immediately rectified. When the entire process is over, a detailed examination of all the records will be done in a separate room. They will all be examined under a flash light and the expert will be able to find out the tiniest of defects from the

way in which they reflect the light. They will also be tested by playing. Thus after both visual and aural examination every record will be labelled and pronounced fit for marketing. In spite of the enormous precautions taken at every stage, numbers of mistakes usually arise during record pressing. Hot pressing or cold pressing is a very common defect. There may be bedding faults in the hydraulic press which will give rise to chipped edges, pimples, lack of definition and so on. A careful watch is kept over all these defects at every stage and records are rejected even for the smallest defect.

The reproduction of sound from the finished record is again done by acoustical and electrical methods. Everyone will be familiar with the acoustic gramophone which is available in the market in various models. The old model gramophones used to have their large horns projecting outside from the sound box. Nowadays they are concealed in cabinets. The driving mechanism for the turn-table is a motor of the spring driven variety with a governor to maintain a uniform speed. The sound box is the most important part of the gramophone mechanism. It consists of a needle arm known as the stylus bar which grips the needle at one end. The other end of the stylus



Fi . 27
Sound Box.

bar is attached to the middle of a flexible diaphragm fixed in the sound box. The diaphragm was made from mica sheet in the earlier days. Now aluminium is used for its construction. From the outside of the diaphragm starts the tone arm which is really the neck of the horn. The tone arm is so constructed that the sound box can be thrown back for easy insertion of the needle. The record is placed upon the turn-table which is covered with

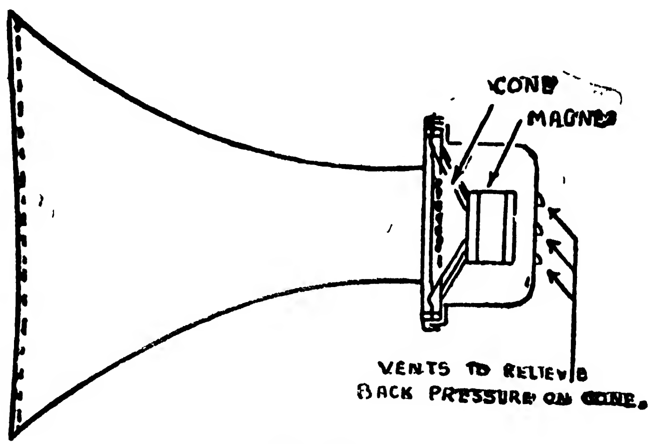


Fig. 28
Loud Speaker.

velvet or felt to prevent scratches to the record. The spring is wound by a key and the turn-table is made to rotate. The flexible tone arm with the needle is brought back into position and the needle is made to follow the spiral groove from the outside of the record inwards. As the needle moves horizontally to and fro while going along the groove the diaphragm is made to vibrate in the same way. The diaphragm thus produces pressure changes in the air in front of it. These pressure

changes are propagated through the horn and the sound is reproduced. When the reproduction is done electrically the needle is made to act directly on an armature coil instead of the diaphragm. When the armature coil which is pivoted between the pole-pieces of a magnet vibrates varying current is generated. This is amplified to the desired extent and sent to a loud speaker. The loud speaker diaphragm then reproduces the sound. This arrangement is called the electrical gramophone. It has been designed to act as an adjunct to the radio set. These electrical gramophones are used invariably in all big hotels to provide entertainment.

CHAPTER XV

FILM RECORDING.

Though the thrill of hearing music along with pictures on the silver screen was a long-felt demand it was not accomplished till 1925. The production of sound-films was made possible as a result of concentrated technical effort on the part of scientists for a very long period starting from the famous Edison. De Forest, the discoverer of the triode radio valve and Theodore Case, the discoverer of an illuminating source which fluctuated in conformity with the wave-form of electrical speech currents, are the other two prominent scientists who made commercial development of talking pictures possible. Before sound-films actually came into existence a trial was made by combining the gramophone disc and the silent film. In this method since picture and sound remained in separate media it gave rise to a number of difficulties. Unless the two were made to run in step with constant speed perfect synchronisation could not be secured. Lack of synchronisation led to very awkward results. For instance, when a person was shouting from the disc his lips remained closed in the picture. Even when synchronisation was achieved if a film break happened it brought complete disaster. Other difficulties were also experienced in combining them. The size of the reels of film had to be determined by the size and speed of the discs. This made editing the picture

extremely difficult. Further the disc records were found to wear out more quickly than the films. Thus the general inflexibility of this sound-on-disc method soon killed it.

The scientists then had no other alternative left except to record the picture on the disc or the sound on the film. The former was out of the question and thus began the search for suitable devices to record sound by photography. For under-standing these devices a knowledge of the principles underlying kinematography is necessary. Celluloid on which the picture is recorded is a transparent substance. It is dissolved in certain volatile liquids and the solution is allowed to dry in the form of a thin film. Lengths of this film are cemented together and coated with photographic emulsion, which contains silver bromide as the active element. The film is usually cut into widths of 1⅜ inches and lengths of 400 feet. As it is highly inflammable it must be packed and handled carefully. Before it is fed to the camera it is perforated by means of a machine which contains a series of evenly spaced punches. The perforated film is then exposed in the camera. Moving pictures depend upon the phenomenon of persistence of vision. The time for which the impression of an object persists on our retina has been variously estimated by different investigators. For practical purposes it may be taken to be one sixteenth of a second. The camera will contain an intermittent mechanism by which sixteen successive picture spaces on the film can be presented to the lens in one

second of time. Before the film reaches the intermittent mechanism it passes over a sprocket wheel, the teeth of which fit the perforations. This sprocket pulls the film out of the top spool and delivers it to the intermittent mechanism. It next passes over another sprocket and goes into the receiving spool. The camera can also be turned in any direction by another suitable mechanism. There is a shutter which cuts off the rays of light from the film during the time the portion of the film is being moved to bring another portion under the action of the lens. The exposed film is then developed by immersion in solutions of chemicals, the action of which is to reduce the silver bromide to metallic silver. This process of developing a considerable length of film is done by special appliances. When the development is complete the film is rinsed in running water, and then immersed in a solution which dissolves out the unexposed silver bromide. This operation is called 'fixing' the image which would otherwise be impermanent. After another washing in water the film is dried and a positive print is obtained in another film. This is also done by a machine. The printing mechanism is exactly similar to that in the camera. Then comes the last stage in kinematography which is to project a highly magnified image of the positive picture on the screen. The projector is again similar in principle to the camera. It contains the same two spools, intermittent mechanism, sprockets and the shutter. In addition it contains a lamp-house where an arc lamp is used as the source

of illumination. The light from this is first concentrated before it is thrown on to the film. After it has passed through the film it is again condensed and projected on to the screen. All these are done by an optical system containing lenses.

Sound also must be recorded on the film in a similar manner. For that a method of modifying the light falling on the sensitive film in such way that the modification will correspond to a succession of sounds must be devised. That is, the fundamentals of sound, namely volume and frequency must be recorded as variations of light and shade on the film. The picture space on the film must be reduced to give room for the sound track. Though the film is cut into 1-3/8 inch width, the picture space is only 1 inch in width. A space of approximately one-tenth of an inch is usually left over for the sound track in commercial films. For recording the sound track, the sounds are first received by a sensitive microphone and the pressure variations are converted into electrical current variations. They are then amplified by suitable radio valve amplifiers. These amplified microphone impulses are then converted into light variations. Two methods are in use in this conversion of electricity to light. They are known as the "variable density" and "variable area" methods. In the first method, a light beam of constant width is projected upon the film and the intensity of light and therefore the exposure is varied by the microphone currents. When the film is fed forward at an absolutely uniform speed

the variation of intensity in the first method will be recorded on the continuously moving film in the form of a band of varying blackness. In the second method the resulting track will have the appearance of a serrated edge of uniform intensity adjacent to a transparent area.

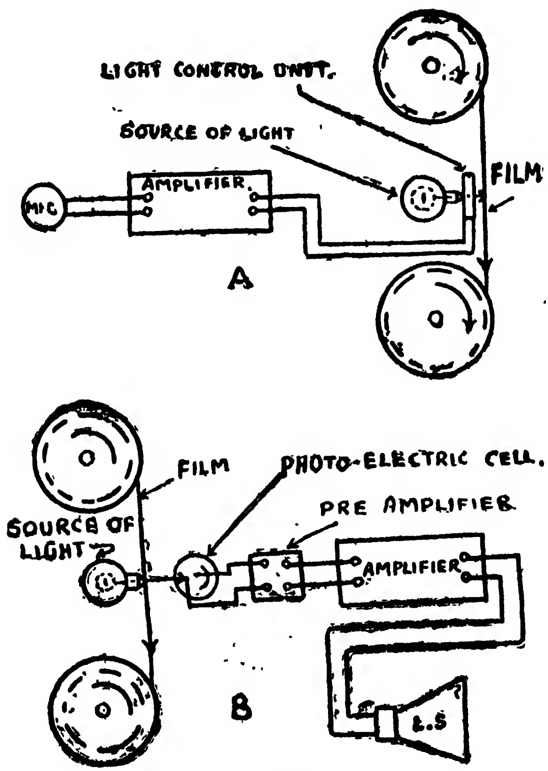


Fig. 29
Photographic recording and reproducing systems.

To secure the fluctuations in the beam of light in conformity with the wave form of electrical sound currents, various devices are employed. The source used for the variable intensity method

was devised by Theodore Case. This is a glass tube filled with an inert gas such as Helium at a very low pressure containing two electrodes. The light is produced by bombardment of gas molecules by the electrons radiated from the cathode and the intensity of the light varies with the voltage applied to the tube. To this lamp the microphone impulses are fed and the variations in its intensity are recorded on the film. In the "variable area" method an oscillograph controlled by the microphone currents is interposed between a light source and a slit of fixed dimensions. The light from the source is reflected on to the slit by the mirror of the oscillograph. Till recently in America and Britain an oscillograph of the Duddel type was in use while in Germany they preferred a cathode ray oscillograph. Thus with either of these two devices the sound record is made near the edge of the film simultaneously with the cinema picture which guarantees perfect synchronisation between the sound and the picture. Recently the Bell Telephone Laboratories have developed a sound recording system which utilizes the "variable intensity method" and the Wente "light valve". Light from a lamp of constant brilliance is made to pass through this "light valve". This light-valve devised by Wente consists of a narrow stretched loop of aluminium tape formed into a slit situated in the gap of an electro-magnet. Sound currents from the microphone and amplifier flow in the loop and cause it to open and close in accordance with the current variations. This varies the amount of light passing the slit and thus the film receives a varying exposure.

The sound recording technique is very elaborate as it involves co-ordination with various other factors such as scenario, script, photography etc. The first detail to be carefully adjusted in the recording technique is the position of the microphone. Music heard distantly must also sound as though it were so heard. Further when a number of persons sing the loudness of the respective voices must be in accordance with the size of the film image. One of the common faults is the location of the microphone too near the artists. It is necessary to determine the average microphone position for various visual positions by trial beforehand. Sometimes the sound recording Engineer adopts trick positions for the microphone. It is either disguised as a desk-lamp or a flower vase or a telephone. The microphone is governed by volume control mounted upon a panel called the mixer, from which in turn the sound is passed by special cables to the recording amplifier and thence to the recording camera, where it is photographed upon the film. For controlling the recording amplifier the recording engineer should perceive the tone-value and the perspective and appreciate rapidly and accurately the fine shades of the sounds recorded. In this he will be helped by a musical director. When a number of instruments are recorded proper orchestra balance must be maintained for good recording.

Before examining how music is reproduced from a sound film let us consider the device known as the photo-electric cell, which is also termed

the "electric eye." This is a device which when actuated by variations of light will set up electrical impulses. It converts light into electric current. It bears a close resemblance to a radio valve. We know that when the filament known as the cathode in the radio valve is heated electrons are emitted. But in the photo electric cell when a ray of light falls on the cathode electrons are emitted. The amount of the electronic emission under the influence of light depends upon the nature of the material composing the cathode and the amount of light incident on the cathode. There are two classes of this type of cell, namely, the vacuum type and the gas filled type. In the former there will be a metal loop in the centre of the vacuum bulb which forms the anode. The inside of the bulb will be coated with a layer of potassium hydroxide leaving a small window in front of the cell for light to enter. Usually the layer of potassium hydride will be upon a silver layer and the two will serve as the cathode. When a light beam falls on the cathode of the cell through the window electrons are emitted and a current passes between the anode and the cathode as in the radio valve. This current will be proportional to the incident light. Cells which employ lithium or sodium or rubidium in the place of potassium are also common.

In the second type the bulb will contain an inert gas like argon; otherwise its construction is similar to the vacuum type of cell. The current flowing between the anode and the cathode in the second type will be magnified by the passage of the

primary electrons through the gas in which they produce secondary electrons. So gas filled cells are much more sensitive than the vacuum cells. Before these photo electric cells came to existence selenium cells were in use. Selenium has got the property of altering its electrical resistance when light falls on it. There is no emission of electrons here, as in the photo electric cells. The alteration of its electrical resistance is made use of in the conversion of light to electricity. Selenium cells often break down during use particularly at high frequencies. Photo electric cells on the other hand are free from this disadvantage. But for better response of selenium to low illumination it would have been completely ousted by the photo electric cell long ago.

For reproducing music and showing pictures the film will be made to run from one spool to another before two illuminants, one for picture projection and the other for throwing a small beam of light on the sound track. While silent projectors are run at 16 pictures per second talking picture projectors will be run at 24 pictures per second. The speed of the talking pictures must be kept constant to a high degree of accuracy. We have already noticed the construction of the intermittent machanism and the shutter in connection with the silent picture projection. So we will now go on to see how music is reproduced. The light falling on the sound track after being intercepted by the film is made to fall on the photo electric cell. The variations in

the photoelectric cell current, which will correspond to the original microphone current variations at the recording studio, are then amplified by a valve amplifier. They are reconverted into sound waves by means of a loud speaker.

Lastly we shall see how the recording of sound is done by the magnetic method. This method is of recent date. It involves the alteration of residual magnetism of a steel tape according to sound pressures. A great advantage of this record is that it may be reproduced almost immediately after it has been made. For recording, the microphone currents are passed through a small electro magnet, the chisel ended poles of which embrace the steel tape which is being pulled at a uniform speed. As it runs past the electro magnet it gets magnetised transversely and the residual magnetism along its length fluctuates in conformity with the microphone currents. For reproduction this tape is passed between the poles of another electro magnet at the same uniform speed. The fluctuations in the impressed residual magnetism will induce corresponding currents in the electro magnet which are then magnified and passed through a loud speaker to reproduce the original sound. All radio broadcasting companies employ this method of recording sound.

CHAPTER XVI

BROAD-CASTING.

Radio broadcasting is the art of transmitting sound waves of music and speech over the earth's surface in all directions. Unaided sound waves travel very slowly and die out soon after spreading a few hundred feet. To take these waves over huge distances was considered an impossibility till Clark Maxwell predicted the existence of electric waves and Hertz established them experimentally. Sir Oliver Lodge, Sir Jagadish Chandra Bose, Marconi and others succeeded in showing that these waves could be used for the transmission of sound waves. With the discovery of the thermionic valve by Fleming and its improvement by De Forest radio broadcasting became an accomplished fact, opening up a vista of commercial and cultural possibilities.

Electric waves are waves in ether while sound waves are waves in air. The former travel with the velocity of light at the rate of 186,000 miles per second in ether while sound waves travel only at the rate of 1120 feet per second in air. Electric waves are also produced by vibrations like sound waves. They have their origin in the vibration of very minute particles of electricity known as "Electrons." The frequency of this vibration is inordinately high. The arrangement made for making the electrons vibrate and start a train of waves in ether is known as an oscillatory circuit.

The frequency of the electrical vibrations has been found to depend upon two electrical quantities in the circuit known as 'Inductance' and 'Capacity.' By varying these the frequency of the electric waves can be altered at will. The frequencies used for transmission normally range from 20,000 to 3,000,000 cycles per second. The analogy of sound waves was used above only to understand the terms frequency, wave length and velocity used in connection with wave-motion in general. These waves are entirely of a different nature from sound waves. Sound waves have nothing to do with electricity.

Only electric vibrations which do not decrease in amplitude are used for broadcasting and the waves produced by these vibrations are called "continuous waves". In a broadcasting station a network of wire will be erected at a considerable height from the ground. This is known as the aerial. It will be connected to the oscillatory circuit. Three methods are employed to produce undamped high frequency oscillations in this circuit. In one method a carbon arc lamp will be connected to the circuit. In the second method an alternating current generator will be used in its stead. Both these methods are now superseded by the thermionic valve transmitter.

The thermionic valve is the backbone of both radio transmission and reception. It will resemble an ordinary electric light bulb. The earliest type consisted of a filament and a metal plate. When

the filament is heated to incandescence by passing an electric current it gives off electrons. The rate at which these electrons are given off depends on the temperature of the filament. The speed of these electrons is enormous. The electrons are simply negatively charged particles. When the plate is positively charged the electrons are attracted by the plate in accordance with the law that unlike electric charges attract. This type of valve is known as a Diode valve. De Forest showed that the efficiency of this valve could be increased enormously by the addition of a metallic mesh known as the grid between the filament and the plate. The grid when suitably charged was found to control the electron emission far more efficiently than the plate. Later on valves containing four and five electrodes came to be used for special purposes.

In the early days of wireless, transmitting stations were not very powerful. With the discovery of the valve this defect was removed. We will now see how the valve is used to produce high frequency electric vibrations. Let us suppose the valve is connected with the two other components namely, the inductance and the condenser with suitable batteries for heating the filament and giving positive charge to the plate. The filament on becoming hot will emit electrons and these will be attracted by the plate and a steady current will flow in the circuit. But we want an oscillatory current in the circuit for producing electric vibrations. The third electrode in the valve namely the grid does this

function. It is made to regulate the flow of electrons between the filament and the plate. By connecting a suitable coil between the grid and the filament,the steady plate current is made oscillatory. The oscillations then make the aerial start up waves in the ether. The length of these waves is controlled by adjusting the values of the inductance and the capacity of the condenser. In a broadcasting station several such valves will be connected together to supply enormous energy for these waves. The positive charge on the plate must also be very high. To do this thousands of volts of direct current will be necessary. Direct current is not generated at such high voltage; only alternating current is generated. The valve is again useful to convert this high power alternating current into direct current. Diode valves are used for this purpose.

Then comes the question of how to make these waves convey the message from one station to another. In wireless telegraphy the message is conveyed by the Morse code. For this the waves are sent not continuously but in discrete wave-trains. These wave-trains according to their wave-length are made to represent the dots and dashes. But in radio communication otherwise known as wireless telephony the continuity of the wave is retained but its amplitude is made to vary with time in such a way that the wave form of the variations is a reproduction of the acoustic wave form of the sounds which form the message. In a broadcasting station the musicians will be asked

to sing before a microphone in a sound proof room. The microphone is so constructed that the sound waves falling on it will produce variations in the electric current flowing through it. The variations

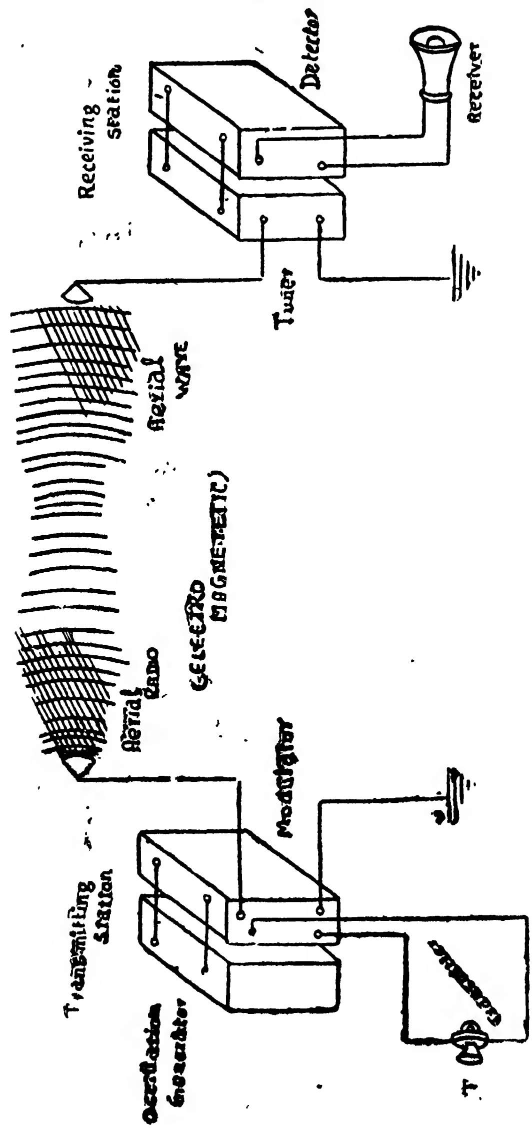


Fig. 30
Diagram showing the principle of broadcasting.

in the microphone current will be very feeble. They are magnified suitably. After magnification they are made to control that is to modulate the ether waves spreading out from the aerial. The apparatus that does this function in the transmitter is known as the modulator. This is again a kind of valve. The action of the modulater can be understood by an analogy. Suppose a steady stream of water is flowing out of a hose which has a nozzle of adjustable width. As the stream of water is pouring if the diameter of the nozzle is varied, the width of the stream will also conform to that size. In a similar way the "continuous waves" or "carrier waves" are modulated by the microphone currents.

These modulated waves spread in the air in all directions. It may be wondered how these waves follow the curvature of the earth and pass round it. Heaviside gave an explanation for this. He showed that the earth must be surrounded by a spherical conductor which acts as a mirror for these waves. It is well known that the atmosphere is always in an electrified condition. This was investigated by a number of scientists. In the course of that investigation Heaviside found his explanation for the propagation of these waves being confined to a particular height above the earth. All matter is formed by a mixture of what are known as "Electrons" and "Protons"; one is negative electricity and the other is positive electricity. Due to a number of causes the atmosphere is split into these electrons and protons. This process is

known as ionisation or electrification. At approximately sixty to seventy miles above the earth's surface it has been found that there is a well-defined layer of ionised atmosphere. Recently another layer similar to this was also found. The former is known as Heaviside layer and the latter as Appleton layer. These two ionised layers reflect the waves and make them follow the earth's curvature. But for these layers radio transmission and reception would not have been possible for great distances. There are disadvantages also due to the electrified atmosphere. For instance, atmospherics which are a great nuisance in wireless reception are due to the abnormal electrical conditions in the atmosphere.

When these modulated waves fall on the aerial erected at the receiving end, they set up oscillations in it. The function of the wireless receiver is to demodulate these oscillations into low frequency currents with which the loud speakers are to be operated. In general the receiver consists of four distinct parts or stages. In the first stage, the set is tuned to receive these waves. Then the high frequency oscillatory current generated in it is amplified without changing its form. This is the second stage. In the third stage the amplified current is sent through a detector for demodulation. After that there is another amplifier which amplifies the low frequency demodulated current. Then it is converted back into sound by a loud speaker. Of these stages detection is the most important. The fluctuations of the current will be very rapid

extending to a million times per second. The diaphragm of the loud speaker or head phones will not follow these rapid current variations. So the diaphragm is made to follow only the variations in the maximum strength of the current in one direction. This is accomplished by the detector or rectifier. In the early days of wireless telephony a device known as crystal detector was used. It consisted of a pivoted metallic conductor resting lightly on the surface of a crystal of galena, corborundum or other minerals. This device offers resistance to the flow of high frequency electric current only in one direction and thus the current also flows only in one direction. It requires very careful adjustment; otherwise it will be completely upset by the slightest vibration. With the discovery of the thermionic valve it has lost its popularity.

The thermionic valve is of great use both in detection and amplification. The detector action of the valve can be compared to the action of the valve in the cycle tube which lets the air pass in but not out. When the grid is positive with respect to the filament electrons are attracted, if negative they are repelled. Thus when high frequency alternating signal voltage is applied to the grid only one half of it is effective in producing current in the plate circuit. The signal voltage is also amplified at the same time. A small change in the voltage applied to the grid produces a large change in the current flowing in

the plate circuit. Separate valves are used for rectification and amplification. Before connecting them in the circuit their behaviour is studied. A curve will be drawn to show how each valve works under different conditions. The shape of its various portions will enable us to make it perform its many different functions. Sometimes valves containing a small amount of gas are used as detectors because of their sensitiveness. These valves are known as soft tubes. Hard tubes are those valves which contain a very high degree of vacuum. They are very sensitive as amplifiers.

After the receiving set has amplified and detected the weak modulated signal voltages the varying current is fed to a loud-speaker. The function of a loud-speaker is to convert this varying current into sound waves. This is done by making its diaphragm vibrate in accordance with the varying current passing through it. The diaphragm being in contact with the air transmits its vibrations into the air as sound waves. The moving coil loud-speaker is the most widely used. The diaphragm in this will be in the form of a cone. A conical formation is given to secure the necessary rigidity consistent with small weight. The cone will be made of paper or other light material. This is attached to a light coil of wire which is introduced into an annular gap in a powerful magnet. When the low frequency varying current from the valves is made to pass through the coil, the coil and the diaphragm vibrate and set up sound waves in the air. There are a number of

types of this loud-speaker. The cabinet type, the baffle type and the projector type are some of the well known types. The main consideration in the choice of the loud-speaker will be the efficiency with which the conversion is accomplished. The sound waves should be a faithful reproduction of the electrical waves fed into the loud-speaker. The various properties of the different types of loud-speakers are studied before connecting them in the circuit.